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Hydrology and Water Resources

ABSTRACT

Water is a critical component of the resource issues and conflicts of the Sierra Nevada. Almost every environmental dispute in the range involves water as principal or secondary concern. Most human activities have some potential to influence the quantity, distribution, or quality of water.

Rivers of the Sierra Nevada appear to have shown remarkable resiliency in recovering from the gold mining era; however, so few channels were left untouched by historic disturbances that reference streams in a completely natural state may not exist for comparison. Water management structures developed concurrently with hydraulic mining and have since come to dominate the flows of water from the Sierra Nevada. Few river systems in the range have natural flow regimes over much of their length. In most river basins, this active management of the water itself affects the annual water balance, temporal distribution, flood hydrology, minimum flows, and water quality much more than any human disturbance of the landscape. Ironically, the primary benefits to society of water from the Sierra Nevada cause the primary impacts. By trying to serve the so-called highest beneficial uses, domestic water supply and production of food and power, we have caused the greatest impacts.

Watershed disturbance in the form of mining, road building, logging, grazing, fire, residential development, and other uses has altered vegetation and soil properties in particular areas. Where these disturbances have altered a large fraction of a watershed, including areas near stream channels, flows of water and sediment may be changed significantly. Nevertheless, major changes in hydrologic processes resulting from watershed disturbance have been noticed in only a few streams. More extensive changes are suspected, but they have not been detected because of the minimal monitoring network that is in place. Proposed programs for reducing the amounts of fuels in forests have potential for significant aquatic impacts; however, catastrophic wildfire carries far greater risks of grave damage to aquatic systems.

INTRODUCTION

> Water, in all its forms, is indeed the crowning glory of the Sierra. Whether in motion or at rest, the waters of the Sierra are a constant joy to the beholder. Above all, they are the Sierra's greatest contribution to human welfare.
>
> Farquhar 1965, 1

Water is central to the resource issues and conflicts of the Sierra Nevada. Changes in water availability, stream-flow quantity and timing, flooding, quality of surface and ground water, aquatic and riparian habitat, soil erosion, and sedimentation have occurred throughout the range as results of land disturbance and resource management (Kattelmann and Dozier 1991). However, the magnitude of such changes, their relative importance, and the ability of natural and human communities to adapt to or recover from alterations in hydrologic processes in the Sierra Nevada are largely unknown. Concern about degradation of water quality is widespread in public reaction to past and proposed resource management activities. Californians need to know whether their primary water source, the Sierra Nevada, is functioning well in general and what problems need attention.

The Sierra Nevada generates about 25 km^3 (20 million acre-feet [AF]) of runoff each year out of a total for California of about 88 km^3 (71 million AF) or about 28% (Kahrl 1978; California Department of Water Resources 1994). This runoff accounts for an even larger proportion of the developed water resources and is critical to the state's economy. The rivers of the Sierra Nevada supply most water used by California's cities, agriculture, industry, and hydroelectric facilities. The storage and conveyance systems developed to utilize the water resources of the Sierra Nevada are perhaps the most

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extensive hydrotechnical network in the world. Major water supply systems have tapped the Tuolumne River for San Francisco, the Mokelumne River for Alameda and Contra Costa Counties, eastern Sierra streams for Los Angeles, and the Feather River for the San Joaquin valley and other parts of southern California. Irrigated agriculture throughout California consumes more than the annual runoff of the Sierra Nevada and accounts for more than 90% of consumptive use in the state (U.S. Geological Survey 1984; California Department of Water Resources 1994). More than 150 powerhouses on Sierra Nevada rivers produce about 24 million megawatt-hours of electricity per year (see Stewart 1996). Operations of most of the water projects are quite sensitive to fluctuations in climate over periods of a few years. Sierra Nevada rivers support extensive aquatic and riparian communities and maintain the Sacramento–San Joaquin Delta estuary ecosystems (see Jennings 1996; Moyle 1996; Moyle and Randall 1966; Moyle et al. 1996; Erman 1996).

Perhaps the most common perception of water from the Sierra Nevada is no perception at all, merely benign ignorance. For many, water is something that appears at the kitchen faucet, showerhead, garden hose, or is a choice among bottled beverages. Water rarely makes the general news except in times of serious shortage or excess. Agricultural and urban communities of the Central Valley that are dependent on water from Sierra Nevada rivers probably have the greatest direct interest in water issues, but they are chiefly concerned about the amount delivered and how fisheries policies might affect those deliveries. Most residents of the Sierra Nevada are probably knowledgeable and concerned about local water supplies and ground water but are not known to harbor any common misperceptions about the local resource, just a shared hope that there always will be enough water available. People in cities benefiting from water supplies exported from the Sierra Nevada are concerned about quantity and quality of water at the tap, but many are unsure about the source of their water. Visitors to the Sierra Nevada are usually concerned about the aesthetic qualities of water that they see. Environmentally conscious segments of the public may believe the water resources of the Sierra Nevada are substantially degraded. Serious water problems in parts of the Sierra Nevada and throughout the country may be extrapolated and perceived as occurring throughout the Sierra Nevada. For example, if poor logging practices in the Pacific Northwest are initiating landslides and ruining fish habitat, then some people may assume the same things are happening within the Sierra Nevada. Water issues highlighted in popular books (e.g., Reisner 1986; Postel 1992; Doppelt et al. 1993; Palmer 1994) are often assumed to apply to the Sierra Nevada but may not be of similar severity.

Water flowing from the Sierra Nevada has far-reaching effects. On the western slope, runoff naturally flowed through the Central Valley of California and San Francisco Bay to the Pacific Ocean or, in the south, contributed to Tulare and Buena Vista Lakes. On the eastern slope, streams flowed toward the terminal lakes of the western Great Basin. In all cases, the waters of the Sierra Nevada enriched the lands through which they flowed. In the past century, the fluid wealth of the mountains has been extended well beyond natural hydrographic boundaries through engineering projects to distant agricultural and urban areas. Electricity generated from falling water in the Sierra Nevada and distributed through the western power grid affects distant communities. Crops grown with and containing water precipitated over the Sierra Nevada are sold around the world. The recreational and aesthetic qualities of Sierran rivers and lakes attract visitors from throughout the United States and the world. Artwork portraying water in the Sierra Nevada is found around the globe; for example, a watercolor mural in traditional Chinese style of waterfalls in Yosemite Valley hangs in the Taipei airport as an example of Chinese scenery.

Water has played a critical role in Euro-American affairs in the Sierra Nevada since the discovery of gold in a channel leading to a water-powered sawmill in 1848. Water was essential to large-scale gold mining and processing. Water development for mining led to one of the nation's earliest major decisions in environmental law (that halted hydraulic mining) and to our intricate network of hydrotechnical structures that transfer water from the Sierra Nevada to farms, cities, and powerhouses. Conflicts over water from the Sierra Nevada are likely to be a continuing part of the California scene. Water is simply too valuable to society and all forms of life to be anything but a high priority for resource policies and management. Water eventually emerges in almost all environmental disputes, even when the debate starts on some other distinct issue. All parties to the dispute can usually agree that water is an influence on or is influenced by the original issue. Water is tied to all other issues considered by SNEP, with some links more obvious than others, but it is literally an integral component of the ecosystem approach.

GENERAL STATE OF KNOWLEDGE

Despite the importance of water to California, there have been remarkably few integrative studies of water resources in the state or the Sierra Nevada. State agencies have issued reports about statewide water matters for more than a century (e.g., Hall 1881; Conservation Commission 1913; California Department of Public Works 1923). The first California Water Plan was released by the Department of Water Resources in 1957. Originally a description of proposed water projects, updates to the California Water Plan have evolved into a more thorough evaluation of water supply, demand, and management (e.g., California Department of Water Resources 1994). Comprehensive descriptions of water in the state appear in books by Harding (1960), Seckler (1971), and the Governor's Office of Planning and Research (Kahrl 1978). The history of water development in California is treated by Hundley (1992). The condition of California's rivers is assessed by the California State Lands Commission (1993). Possible scenarios of the future of water resources in California have been developed by the California Department of Water Resources (1994) and the Pacific Institute (Gleick et al. 1995). Although all these books deal with the Sierra Nevada as a critical part of the California waterscape, and books devoted to the Sierra Nevada (e.g., Peattie 1947; Lee 1962; Johnston 1970; Webster 1972; Bowen 1972; Palmer 1988) at least mention water resources, a thorough treatment of water in the Sierra Nevada has yet to be written. Thousands of articles, chapters, and reports address the various aspects of hydrology and water resources in the Sierra Nevada, but there has been little synthesis of this vast work. The isolated, topical work provides a wealth of information about specific details but does not inform society about the context of that work at the scale of the mountain range or even of a river basin. In addition, there are serious gaps in the collection of information about Sierra Nevada waters. Although knowledge is far from complete for most aspects of the water-resource situation, the most troubling gap is the virtual absence of experimental research on hydrologic impacts of land management activities. Because of this near lack of local research, we usually had to infer the likely consequences of disturbance from studies done outside the Sierra Nevada. In addition, the state does not have a thorough description of each river basin that would be adequate for environmental assessments. Comprehensive lists of environmental problems in each river basin do not exist. There is no consistent method for characterizing watersheds. Absence of consistent criteria for evaluating ecological conditions along streams or in watersheds inhibits assessment of management consequences or need for restoration (California State Lands Commission 1993).

OVERALL APPROACH AND SOURCES

This assessment was primarily a literature review augmented with the author's experiences throughout the Sierra Nevada over the past two decades and a few weeks of specific field checking during the SNEP period. The libraries of the University of California and the Water Resources Center Archives at Berkeley, in particular, were critical to the effort. Offices of the national forests in the Sierra Nevada also provided a wealth of documents. Other materials were provided by dozens of agencies and individuals. Newspapers were essential sources of current information. Interviews with agency personnel and private parties augmented the written word. The primary challenges were to compile and synthesize the diversity of material. The quantity and quality of information gathered varied widely between river basins throughout the range. Important sources were undoubtedly overlooked because of ignorance of their existence and inability to actually locate all known sources. One of the critical assumptions of this assessment was that the reported material was indeed reliable. Multiple sources of information that were consistent provided greater confidence in most material. Information was organized by resource, by impact, and geographically by river basin. Use of natural hydrologic areas was a central tenet of this effort. Consideration of nested catchments from headwaters to large river basins provides a logical hierarchy that makes physical and ecological sense. Watersheds are becoming a more common unit of analysis and planning. The California Resources Agency is organizing many of its programs on a watershed basis and has adopted a watershed delineation scheme called Calwater. This system was used in this study and by other parts of SNEP. River basins and major streams of the study area are identified in figures 30.1–30.3.

Attributes of Water

There are several attributes of water and streams that are impacted by management activities. The physical attributes are briefly described in the following paragraphs (see Moyle 1996; Moyle and Randall 1996; Erman 1996; Moyle et al. 1996; Jennings 1996 for biological impacts). The present study did not perform any systematic analyses of these attributes. Such analyses (within the constraints of readily available data) would not provide clear indications of the health of the hydrologic system of the Sierra Nevada. Instead, synthesis of existing analyses originally performed for various other purposes provided the basis of this assessment.

Stream flow (or stream discharge) is the most fundamental aspect of watershed hydrology. Stream flow will usually be addressed in this assessment just as a concept: volume of water passing by a point on a stream over some period of time. Fortunately, this concept is also measured at hundreds of sites within the SNEP study area. However, the number of sites with data useful to this study is much more limited, numbering in the dozens. Most stream-flow measuring stations are located in association with some water management project rather than for scientific study. Therefore, most information is available on highly regulated streams that suggest little about hydrologic response to changes in the landscape other than the direct manipulation of water in the channel. Gauges on unregulated (often called unimpaired) streams often have short or incomplete records or are sited in locations inappropriate for any particular after-the-fact study. The number of such gauges in the Sierra Nevada has decreased with time as costs have risen. Stream gauging stations are operated by the U.S. Geological Survey, utilities, irrigation districts, and a few other public agencies. Many of the records are published as daily values in annual volumes by the U.S. Geological Survey (USGS). Most of these records are now available on CD-

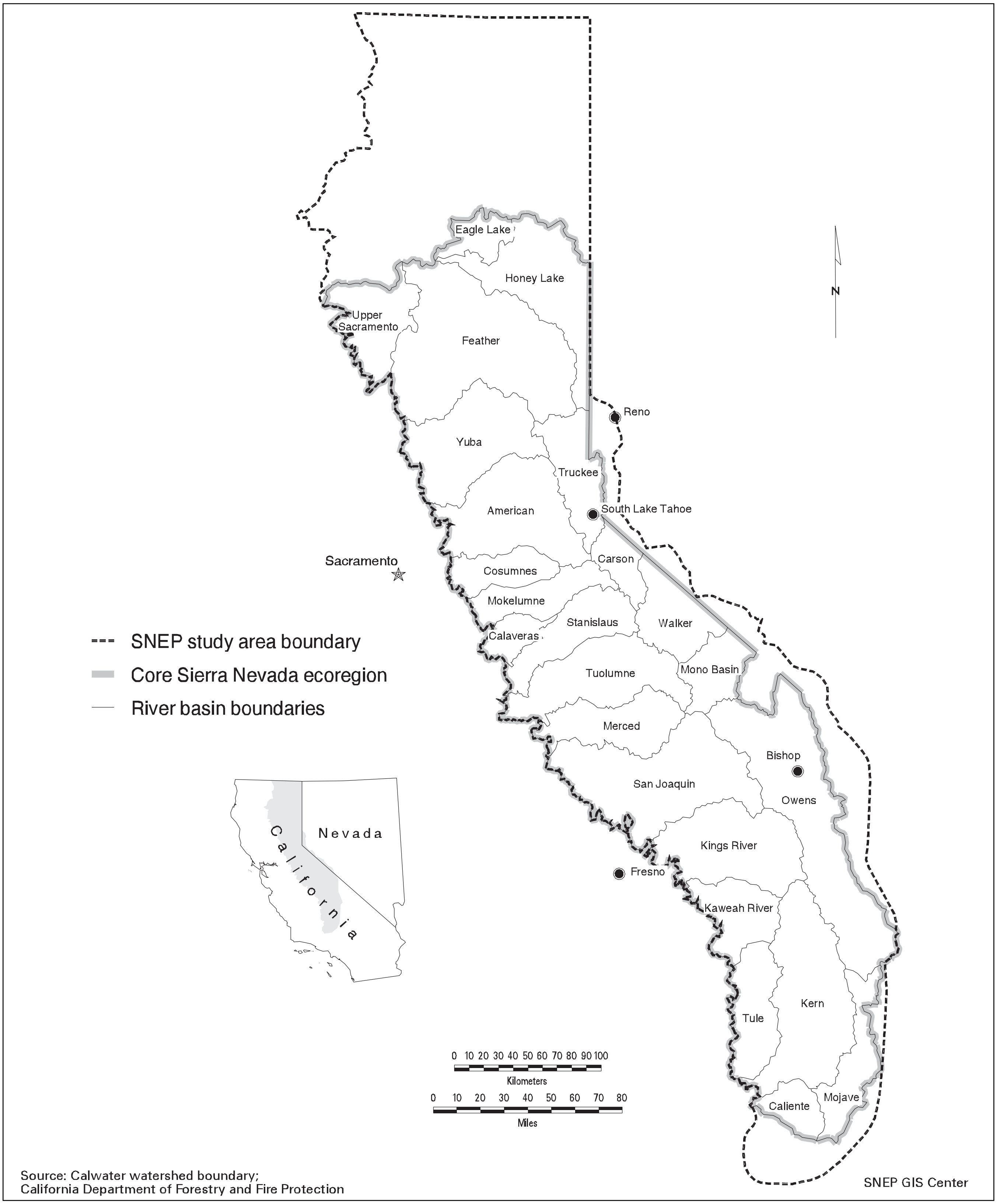


FIGURE 30.1

Major river basins of the SNEP core study area.

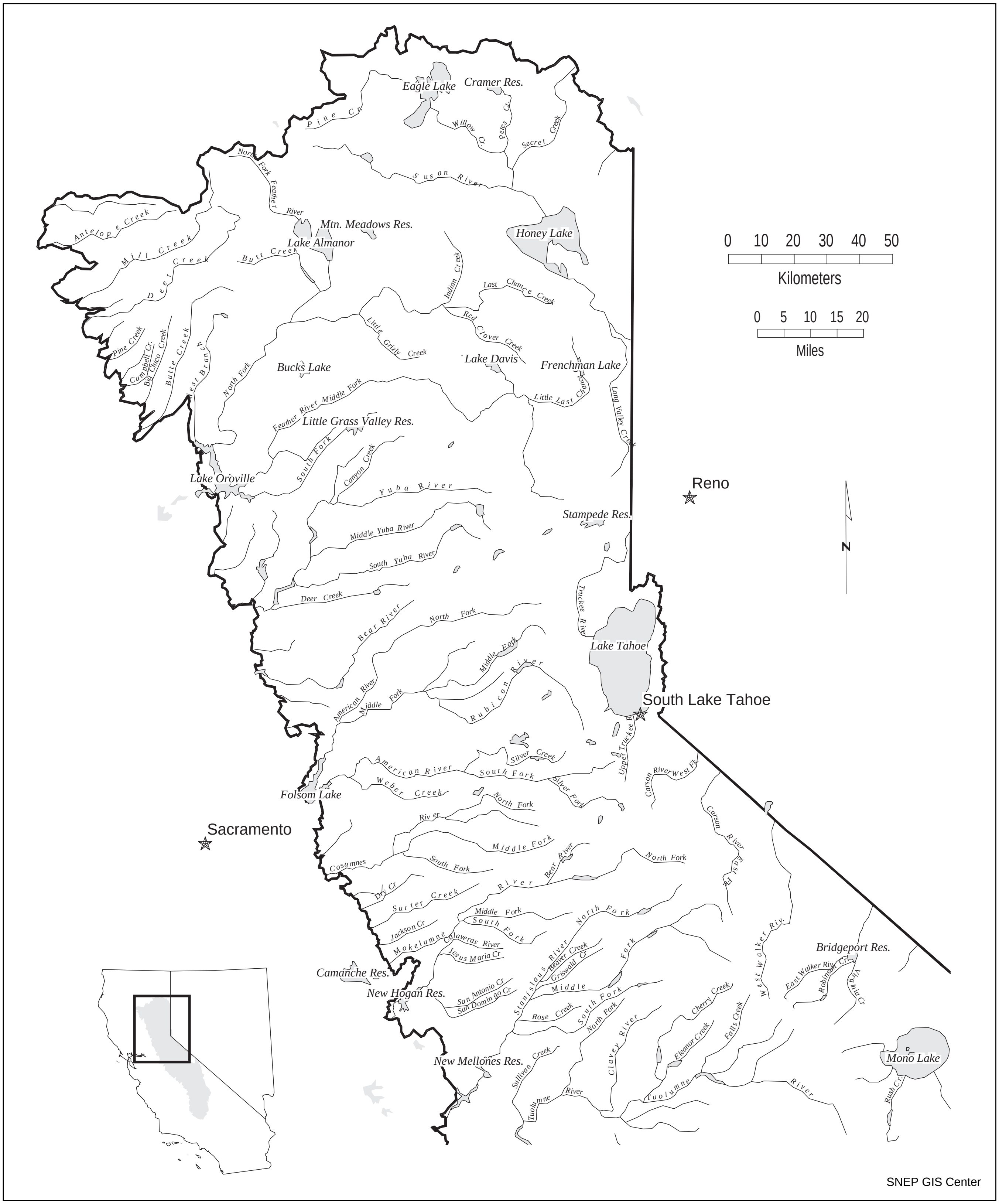


FIGURE 30.2

Principal rivers and streams of the northern half of the SNEP core study area.

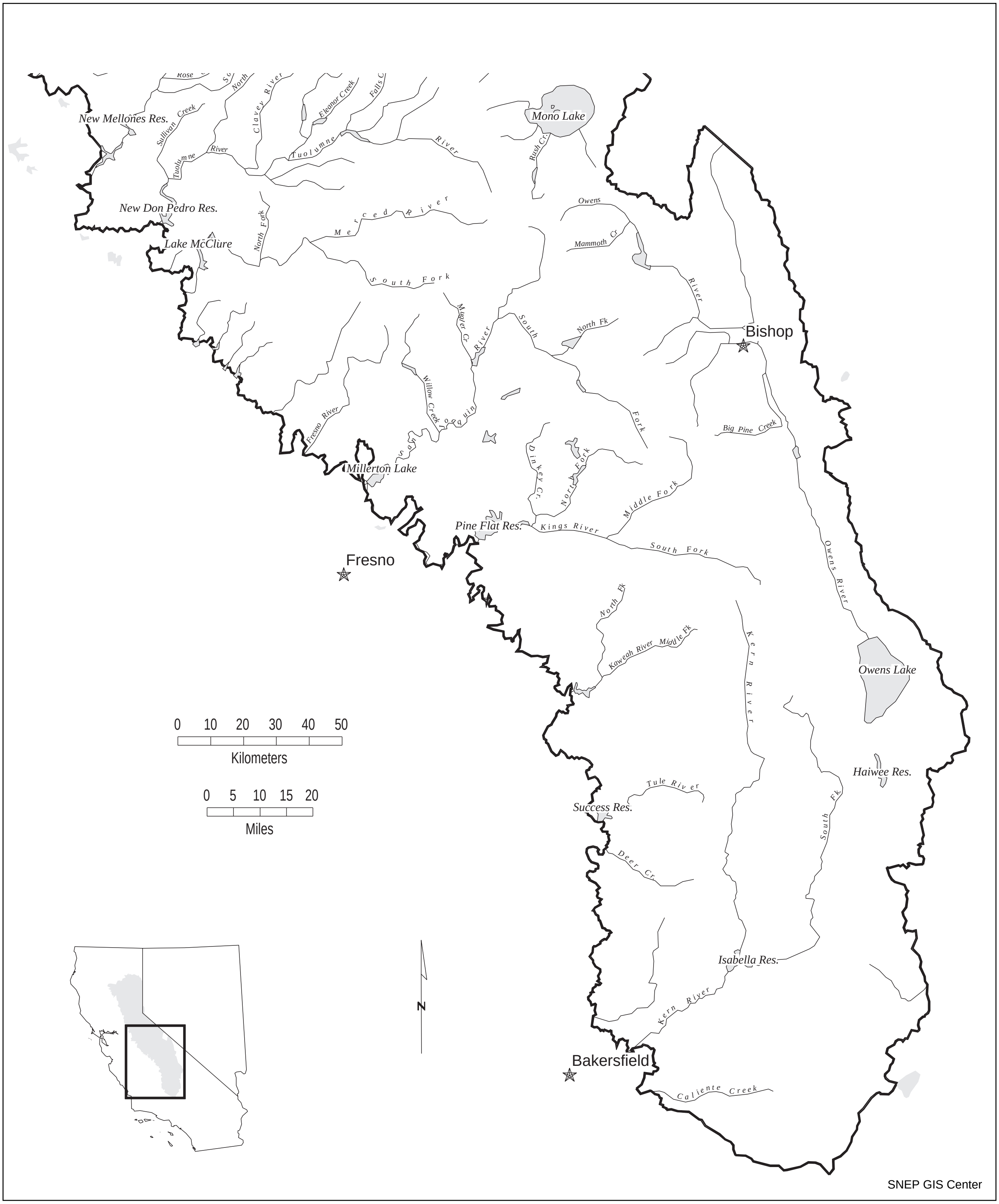


FIGURE 30.3

Principal rivers and streams of the southern half of the SNEP core study area.

ROM from private firms and the USGS. The usual characteristics of stream flow that are studied are the annual volume, distribution over time (i.e., annual hydrograph), maximum flows, and minimum flows. Measurement of flows in natural channels is not a trivial exercise, and errors can exceed 10% to 20% of the measured value (Herschy 1985). Natural variability in all aspects of stream flow can be quite high.

Sediment is the other main constituent of the fluid flowing in streams that we casually call water. Changes in sediment removal, transport, and deposition affect the general nature of stream channels and riparian areas and their biota, as well as affecting human uses of water. Mineral particles eroded from the land surface and transported mostly by flowing water gradually (or sometimes suddenly) move downslope from the mountains. These particles of various sizes are either suspended in the water or bounce along the channel as bedload. Both types of sediment move episodically as the capacity of streams to transport sediment varies with flow velocity. Sediment can be stored in a channel for years (or even centuries) before conditions are right to dislodge and transport it. Individual particles have a discontinuous journey downstream, with intermittent advances of varying lengths interrupted by temporary storage of varying duration. Suspended sediment is sampled at few stations throughout the Sierra Nevada and is a marginal measure of total sediment load. Bedload moving past a point is not routinely measured anywhere in the Sierra Nevada, but it has been measured in special studies (e.g., Andrews and Erman 1986). Repeated surveys of the bottom topography of natural and artificial lakes and calculation of the change in volume over the time interval is the best means of estimating total sediment transport (Dunne and Leopold 1978). However, this technique integrates sediment production from a large area and duration and, therefore, is difficult to associate with particular land-use activities. It is also very expensive.

Most other materials that are found in flowing water constitute the dissolved load of streams. A variety of ions occur naturally in streams, although the waters of the Sierra Nevada tend to have relatively low amounts of dissolved constituents compared with other rivers of the world (e.g., California State Water Resources Control Board 1992a). The chemical quality of streams is routinely measured at only a few gauging stations in the Sierra Nevada. There is also a biotic component of streams, ranging from viruses and bacteria to invertebrates and fish (see Moyle 1996; Moyle et al. 1996; Erman 1996).

Water temperature is another important attribute of streams, particularly with respect to suitable conditions for aquatic life. Some creatures can tolerate only relatively narrow ranges in temperature at different stages in their life cycles. The amount of dissolved oxygen also varies with temperature, decreasing as temperature increases. As with other water quality parameters, temperature is measured at only a few river gauging stations. Stream temperature varies primarily with stream discharge, original temperature of water inputs, exposure to sunlight, geothermal conditions, and temperature of reservoir releases.

Attributes of ground water that are of primary interest and are subject to change are the amount and quality of water in storage. Ground-water conditions in the Sierra Nevada are not routinely monitored in the manner of stream flow. Public utilities that pump ground water for water supply monitor their own wells but do not systematically report their results. Most of the publicly available information about ground water in the Sierra Nevada is from a handful of special studies.

Scale

Consideration of the scale of hydrologic impacts is crucial to understanding how water resources are affected by disturbance. A point of reference is necessary. Usually, some particular point along a stream where measurements are made of flow and/or quality parameters provides the geographic context. Impacts upstream of that point may have some measurable effect at the reference site. Activities in the river channel itself are likely to produce the greatest noticeable impacts in the channel at the point of reference. Activities near the channel in areas with occasional hydraulic connection to the channel will also have direct impacts (i.e., change in water or sediment yield) in the channel under consideration. Such areas may be surface-runoff contributing zones (sometimes called variable source areas) that yield water as sheet flow or near-surface pipe-flow in response to rainfall. At greater distances from main channels or ephemeral tributaries, water resulting from rainfall or snowmelt moves slowly downslope through soil or subsoil. Alteration of hillslope properties at locations distant from the stream channel simply has less opportunity to make a difference at the downslope and downstream point of reference. To restate the typical effect of geographic location on hydrologic impacts, a given disturbance matters less on a ridgetop than adjacent to a channel.

Cumulative Effects

One must also consider the combined or cumulative effects of activities on attributes of water at a point of reference. Altering the local water balance of a small fraction of a watershed or even adding a small quantity of pollutant to a stream usually will not result in any detectable change at some distant downstream point of reference. However, altering many small fractions of the watershed or adding the small quantity of pollutant at many places along the stream will cause a detectable change downstream. Even though each individual impact is insignificant with respect to the whole watershed, their cumulative effects may be dire. An instructive example of cumulative watershed effects occurs in the Lake Tahoe Basin, an easily visualized hydrologic unit in which the lake is the item of reference. Construction of roads, houses, casinos, parking lots, ski runs, septic systems, and so on initially affected only the immediate area of the particular development.

However, at some time, perhaps in the 1960s, there were so many individual disturbances that the nutrient balance of the lake was profoundly changed and algal production increased, with a consequent decrease in lake clarity (e.g., Goldman 1974 and 1990). Similarly, while a small diversion from a stream for irrigation might not be detectable at a downstream point, hundreds of small diversions can totally dry up a stream. Ground-water overdraft is typically the cumulative result of hundreds of small extractions. Therefore, when considering the potential impact of some activity on water resources, one must examine the intensity of the impact, how extensive it is (what fraction of the watershed is affected), the proximity of the activity to a stream channel, what other impacts in the watershed it is adding to, and the degree of recovery from past impacts. These questions of scale are implicitly addressed throughout this chapter.

HISTORY OF IMPACTS ON WATER RESOURCES

Examination of past impacts to streams and rivers helps us understand their current condition. Impacts of Native Americans on the hydrologic system appear to have been minor, largely because of the comparatively small population in the mountains and limited technology. Their deliberate use of fire as a vegetation-management tool would have been the primary agent in altering local hydrology. To the extent that intentional fires removed vegetation, evapotranspiration was reduced, water yields were increased, and surface erosion was increased. The geographical extent, intensity, and frequency of such fires cannot be quantified. Therefore, about all we can say concerning the hydrologic consequences of this activity is that there were some. Areas near to population centers were probably impacted to a greater degree than remote areas. Little is known about water development by Native Americans. Perhaps the best documented projects occurred on Bishop and Big Pine Creeks. Starting perhaps 1,000 years ago, the Paiute built dams and large irrigation canals to irrigate areas exceeding 5 km^2 (2 mi^2) in the bottomlands of the Owens Valley to enhance the growth of native vegetation (Steward 1934; Lawton et al. 1976). More modest water impoundments and diversions were built in the Tahoe basin by the Washoe (Lindstrom 1994).

The discovery of gold in 1848 had swift and dramatic consequences for streams and rivers of the Sierra Nevada. Streams were dammed, diverted, dewatered, excavated, polluted, and filled with debris from enormous hydraulic mines. Removal of trees over large areas for flumes, mine timbers, buildings, and fuel resulted in soil loss, augmentation of downstream sedimentation, and major changes in vegetative cover. Gold mining also led to many innovations in water institutions and engineering. Miners established the principle of priority in determining water rights just as in mining claims. The resultant doctrine of prior appropriation has far-reaching effects in the allocation of water resources throughout the western United States. Acquisition of water for hydraulic mines developed engineering technology and physical works that have had lasting impacts on California's water distribution system. Generation of power for mines and mills led to one of the world's most extensive hydroelectric networks.

Initially, miners worked as individuals on small claims with simple implements. Shallow gravels were excavated and washed with water in pans, rockers, long toms, and other crude devices (Silva 1986). Virtually all streams on the central western slope of the Sierra Nevada were prospected (Averill 1946; Clark 1970). Although the depth of disturbance was limited, these excavations destabilized channel beds and banks and devastated riparian vegetation over a vast area. As the surface gravels were exhausted, more intensive methods required cooperation and consolidation of the miners. Flumes were constructed to carry the summer flows of streams so that beds could be blasted and excavated. Small dams were built so that several hours of discharge could be stored and released suddenly to disaggregate the gravels hydraulically and carry away lower-density sediments in a practice known as booming or gouging. Diversions and flumes were also built to supply water to off-channel claims for separating gold and for ground sluicing where diverted water was used to erode ancient stream deposits (Averill 1946). Natural channels were often totally dewatered to supply maximum flow in an artificial waterway (Pagenhart 1969).

The erosive power of water was marshaled to great effectiveness by containing water within pipes and hoses under high pressure and then directing it at hillslopes composed of gold-bearing gravels (Stanley 1965; May 1970). As an example of the power and water use of hydraulic techniques, flumes and pipes with 120 m (400 ft) of head could deliver about 3.8 million liters (1 million gal) of water per hour through a 25 cm (10 in) nozzle at a speed of about 200 kph (120 mph) (Logan 1948). Sediment-laden runoff from the eroded hillslopes was directed into long sluice boxes, often in tunnels, to extract the gold and then discharged into the nearest creek.

At the peak of hydraulic mining, there were more than four hundred hydraulic mines in operation (Wagner 1970). Hydraulic mining was most prevalent from the Feather River to the North Fork American River (Gilbert 1917; Averill 1946). The largest quantities of material were found in the South Yuba, lower Yuba, Bear River, and North Fork American River (Gilbert 1917; James 1994). Collapse of the English Dam on the Middle Fork of the Yuba (Ellis 1939; McPhee 1993) in June 1883 released almost 18 million m^3 (15,000 AF) of water suddenly and cleaned out much of the stored mining debris in that channel (James 1994). Several of the individual pits excavated more than 75 million m^3 (60,000 AF) of material and flushed it downstream (Gilbert 1917; Senter 1987; McPhee 1993). Channels immediately downstream of the hydraulic pits were usually overwhelmed by the enormous sediment loads and stored the sediments until high-flow events flushed some of the material downstream. Surveys of the 1870s showed accumulations of 30 to 60 m (100 to 200 ft) depth in tributaries to the Bear River (Pettee in Whitney 1880, cited by James 1994). Debris was redeposited throughout the channels, but often formed tailings dams at confluences where channel gradients lessened (James 1994). Temporary reservoirs formed behind these debris accumulations, which occasionally failed catastrophically, releasing large volumes of sediment, perhaps as hyperconcentrated flows. In the early years of hydraulic mining, the upper gravels of the Tertiary river channels were attacked first. After 1870, the lower gravels, which were more strongly cemented than those above, were mined by more powerful methods that moved even more of the landscape (Lindgren 1911). This second phase of hydraulic mining produced coarser sediments and greater quantities of debris than the first period (James 1988).

As sediments moved downstream, valley rivers aggraded dramatically, and coarse sediments were deposited on farms and fields. Thousands of acres of farmland became inoperable under annual deposits of unnaturally coarse sediments (Hundley 1992). As the farmers of the Central Valley gained economic and political power, they were able to successfully challenge the mining interests (Kelley 1959). In 1884, after eighteen months of deliberation in the case of Woodruff v. North Bloomfield, Judge Lorenzo Sawyer of the Ninth U.S. Circuit Court in San Francisco issued an injunction against further discharge of mining debris. This decision held that release of mining waste inevitably damaged the property of others and destroyed the navigability of the Sacramento and Feather Rivers, violating both common and statutory law and interfering with commerce (Hundley 1992).

After hydraulic mining was halted, some of the debris created earlier continued to move through the rivers, largely in pulses during peak flows. Debris that was not entrained during the phase of active stream incision continues to erode into channels and perpetuates the enhanced sediment delivery of the affected streams (James 1988). Many of the small debris dams intended to stabilize mining sediment failed and released the stored material. Large competent dams have effectively stopped transport of upstream sediment to the lower reaches of the main rivers. Even after a century, exposed surfaces in the pits continue to erode through mass failures, gullying, rainsplash, and rill erosion and produce substantially elevated sediment concentrations downstream of the old mine sites (i.e., Senter 1987).

The total volume of mining debris delivered to the Central Valley has been estimated at about 1.1 billion m^3 (900,000 AF) from five rivers, with the Yuba contributing about 40% of that quantity (Gilbert 1917; Mount 1995). Gilbert (1917) also estimated that mining sediment was produced at rates about ten times greater than natural sediment yield from the Sierra Nevada, although these estimates of background rates were highly uncertain.

Mercury used in ore processing is another legacy of the mining era remaining in stream channels. The amount of mercury used in gold extraction in the Sierra Nevada and largely lost to soils and streams has been estimated at 3.4 million kg (7.6 million lb) (Central Valley Regional Water Quality Control Board 1987). Much of this mercury has moved downstream, and some of it may have contaminated mudflats of San Francisco Bay. Large amounts of mercury are still found in stream sediments throughout the Gold Country and are also trapped in reservoir sediments (Slotten et al. 1995). The cyanide process for extracting gold from powdered rock was introduced about 1896 (Clark 1970; Shoup 1988). The degree of water pollution resulting from its use and the earlier chlorination process is unknown.

Underground mining, also called hard-rock, quartz, or lode mining, began shortly after the discovery of gold in streambeds, with the Argonaut mine near Jackson opening in 1850. The Sixteen to One mine in the Yuba River Basin persisted as the main gold mine in California until 1965 and was reopened a few years ago. Hundreds of quartz mines were operated throughout the Mother Lode of the western slope (Jenkins 1948; Clark 1970). The main mining districts of the eastern Sierra Nevada were at West Walker River, Bodie, Green Creek, Virginia Creek, Lundy Canyon, Tioga Pass, Mammoth Creek, Pine Creek, Bishop Creek, and Independence Creek (De Decker 1966; Clark 1970). Both lode and placer deposits were mined in the Kern River drainage beginning in 1851 (Troxel and Morton 1962). Disposal of tailings, mine water, and ore-processing effluent were the main impacts of the underground mines on streams. Although perhaps significant locally, these impacts were minor compared with those of the surface operations.

Dredging was an important source of gold and a major impact on the lower reaches of the main rivers where the Sierra Nevada meets the Central Valley. Large-scale river dredging began in 1897 along the Yuba near Marysville (Logan 1948) and lasted until 1967 (Clark 1970). The largest dredging operations were at Hammonton on the lower Yuba and near Folsom on the lower American. Dredging was also practiced on Butte Creek, Honcut Creek, the lower Feather, the Bear near Lincoln, the Cosumnes at Michigan Bar, the Calaveras at Jenny Lind, the Mokelumne at Camanche, the Tuolumne at La Grange, and the Merced at Snelling (Aubury 1910; Clark 1970). Between 1900 and 1910, dredge capacity increased from about 20,000 m^3 (25,000 yd^3) to 200,000 m^3 (250,000 yd^3) per month (Aubury 1910). Reclamation and revegetation of dredge spoils were concerns as early as 1910 (Aubury 1910).

The development of mining towns put great pressure on local resources, which probably had consequent impact on local streams. Towns sprang up quickly when new strikes were rumored and were successively rebuilt after surprisingly frequent fires. Some towns like Elizabethville in Martis Valley and Summit City near Cisco grew to several thousand people before suddenly collapsing. Development of trails, roads, railroads, and agriculture to support the towns converted forests to bare and compacted soil, which was susceptible to erosion. Overgrazing for food production further altered plant cover and degraded riparian zones. Harvesting of fish and mammals for food and loss of habitat decimated wildlife populations and altered ecological processes (Hinkle and Hinkle 1949; Strong 1984). Demand for wood for shelter and fuel quickly depleted the forests closest to the new towns and then progressively expanded the circle of destruction. Lumber was also needed for underground mine supports, railroad ties, and flumes. In a few cases such as Bodie, lumber and fuel wood were imported from considerable distances. Forests of the Tahoe basin were cut extensively to supply wood for the Comstock silver mines near Virginia City. The Bonanza mines alone consumed 28,000 m^3 (12 million board feet) of lumber and 145,000 m^3 (40,000 cords) of fuel wood per year. An extensive network of skid trails, haul roads, railroads, tug boats, and flumes efficiently removed the forests of much of the Tahoe basin. An estimated 600 million board feet of lumber were buried in the Comstock mines (Hinkle and Hinkle 1949; Strong 1984). More than twenty sawmills in the Middle and South Forks of the American River produced lumber for buildings and replacement flumes for those destroyed by annual floods (Lardner and Brock 1924, cited by James 1994).

The first known miner's ditch was a V-shaped flume about 3 km (2 mi) long built at Coyote Hill near Nevada City in March 1850 (Pagenhart 1969). Later that year, a 14 km (9 mi) long ditch was built by the Rock Creek Water Company, which recovered its investment in just six weeks from the sale of water (Wagner 1970). Natural lakes in the upper Yuba basin were augmented and regulated with crude dams as early as 1850 (Pagenhart 1969). Acquisition and delivery of water to mines became a huge industry that was probably more profitable than mining. If ditches were important to the mining of surficial placer gold, they became critical to the hydraulic mining industry. Large companies built vast networks of reservoirs and waterways acquired through purchase, filing on abandoned claims, court challenges to water rights, and real and implied violence (Hundley 1992).

The levels of investment, labor, and engineering skill devoted to the miners' ditches were impressive. The main supply ditches were 2.4–4.6 m (8–15 ft) wide at the top, 1.2–1.8 m (4–6 ft) wide at the bottom and at least 1 m (3 ft) deep (Wagner 1970). Water was conveyed across valleys and rock outcrops in wooden flumes or iron pipes mounted on trestles (Logan 1948). By 1857, $13.5 million had been invested in mine water systems, with $3 million of that total in Calaveras and Tuolumne Counties (Langley 1862, cited by Shoup 1988). In the 1860s, more than 8,500 km (5,300 mi) of main canals and about 1,280 km (800 mi) of branch ditches had been constructed (Browne 1868; Logan 1948; McPhee 1993). By 1884, the total length of ditches, flumes, and pipelines built for mining purposes reached 12,800 km (8,000 mi) (Wagner 1970). (This figure was probably for all of California.) The South Yuba Canal Company maintained 720 km (450 mi) of waterways at its peak, and the Auburn and Bear River Canal operation included 460 km (290 mi) of ditches. The dam at Meadow Lake constructed by the South Yuba Canal Company in 1858 was 12 m (42 ft) tall and 350 m (1,150 ft) long (Hinkle and Hinkle 1949). By 1880, the California Water Company had twenty-one reservoirs and 400 km (250 mi) of flumes and ditches between the Middle Fork and the South Fork of the American River. At the peak of hydraulic mining activity, there were more than 1,600 km (1,000 mi) of ditches in Nevada County (Kahrl 1978). By the 1870s, artificial reservoirs in the Sierra Nevada stored more than 185 million m^3 (150,000 AF) of water (Pisani 1984). The Eureka Lake and Yuba Canal Company operated four high-elevation reservoirs to supply water to mines near North San Juan, 100 km (65 mi) away (Wagner 1970). In the same region, the North Bloomfield Gravel Company used 55 million m^3 (45,000 AF) of water annually at up to 110,000 liters (30,000 gal) per minute (McPhee 1993) or 227,000 m^3 (184 AF) per day and had reservoir storage capacity of 28 million m^3 (23,000 AF) (Pisani 1984). The company's Bowman Dam was 22 m (72 ft) tall in 1876 and was raised another 7 m (23 ft) to increase storage as the mine's water demand increased. The Cherokee mine in Butte County used up to 150,000 m^3 (123 AF) of water per day (Hundley 1992). Abandoned ditches have become naturally revegetated but can still affect runoff processes today (Pagenhart 1969). Occasional failure of both maintained and abandoned ditches can cause local debris flows and gully erosion.

Water Development

Water was also sold for domestic use and for water power for lumber and stamp mills, air compressors, and Pelton-wheel electric generators after 1890. Increasing scarcity of wood for fuel led to the use of high-pressure water for mechanical power. By the mid-1880s, most of the large hard-rock mines were using water power instead of steam power. The first known use of electrical generation for operation of mining and milling equipment in California occurred in El Dorado County in February 1890 (Logan 1948). After hydraulic mining was halted in 1884, many of the canals were acquired by irrigation districts and later by power companies. The Nevada Irrigation District still relies on reservoirs and canals built for mines in Nevada County. The Pacific Gas and Electric Company eventually took over 520 separate ditch enterprises and their water rights and facilities. By the 1890s, the log-and-brush and earth-filled dams of the miners were replaced by more substantial concrete structures (Pisani 1984). Irrigated agriculture in the foothills occupied about 36 km^2 (14 mi^2) around Auburn and Placerville in 1880 (Pisani 1984) and grew substantially in the following decades (see Momsen 1996).

The vast network of artificial channels built for mining allowed the hydroelectric industry to take off as soon as water-powered generating technology became available. A dam on the American River at Folsom begun in 1866 that was originally intended for hydromechanical power later provided water for the first transmission of hydroelectricity out of the

Sierra Nevada. This project at Folsom began supplying power for an electric railroad in Sacramento in 1895 (Fowler 1923). After its first dam failed in 1892, a hydroelectric power plant on the South Yuba was completed in 1896 and supplied electricity for the Grass Valley and Nevada City area (Pacific Gas and Electric Company 1911). In the next two decades, dozens of hydroelectric facilities were completed throughout the Sierra Nevada: Knight's Ferry-Stanislaus, 1895; Electra-Mokelumne, 1897; Kern 1897; Newcastle-Bear, 1898; Colgate-Yuba, 1899; Farad-Truckee, 1899; Phoenix-Stanislaus, 1901; American, 1903; De Sabla-Butte 1903; Bishop Creek No. 4, 1905; San Joaquin No. 3, 1906; Kittredge-Merced, 1906; La Grange-Tuolumne, 1907; Big Creek No. 1, 1913; Kaweah No. 3, 1913 (Pacific Gas and Electric Company 1911; Fowler 1923; Coleman 1952). Independent companies were quickly merged and integrated, and multiunit projects were developed by the two companies that emerged from the consolidation battles, Pacific Gas and Electric and Southern California Edison. The Crane Valley project involving Bass Lake and Willow Creek was developed between 1900 and 1920. On the North Fork of the Feather, Pacific Gas and Electric was filling Lake Almanor and Bucks Lake by 1928 (Coleman 1952). The Big Creek project, started in 1911 by the Pacific Power and Light Corporation, was completed by Southern California Edison in 1929 and included three large reservoirs, eight tunnels, and five powerhouses (Redinger 1949).

In addition to the dozens of hydroelectric projects taking advantage of the mining waterways, three immense municipal-supply projects began as mining faded out. A scheme to develop Lake Tahoe as a water supply for San Francisco was proposed even earlier, in 1866, but failed to find support (Strong 1984). The city of San Francisco itself began prospecting for water in the Sierra Nevada as early as 1886 (Kahrl 1978). The city remained focused on the Tuolumne River with a dam at Hetch Hetchy Valley despite other feasible alternatives (Freeman 1912; Jones 1965). Largely because the project was in a national park, the proposal generated enormous controversy; however, the city prevailed with congressional approval of the Raker Act in 1913. Hydroelectric generation on a subsidiary portion of the project began in 1918, but water deliveries to San Francisco did not begin until 1934. The Owens Valley project of the city of Los Angeles was constructed more rapidly. After the general concept arose in the 1890s, construction bonds were approved in 1907 and work began in 1908. The project was operational in 1913, when Owens Valley water reached the San Fernando Valley. An extension into the Mono basin was built between 1934 and 1940. A second aqueduct was completed in 1970, enabling greater export of surface water and pumped ground water. The controversies created by the Owens Valley diversions have been described by dozens of authors (i.e., Chalfant 1922; Nadeau 1950; Kahrl 1978; Hoffman 1981; Kahrl 1982; Reisner 1986; Walton 1992; Davis 1993; Sauder 1994). By comparison, political conflict was almost absent in the Mokelumne project of the East Bay Municipal Utility District. Work began in 1923, and Pardee Reservoir began filling in 1929, with water deliveries to Alameda and Contra Costa Counties that same year (Harding 1960). These systems deliver large volumes of water to distant communities with a large net production of electricity. Hydroelectric power production has been a key source of revenue in the financing of water projects in the Sierra Nevada.

The federal government's involvement with water in the Sierra Nevada began with the Newlands Reclamation Act of 1902, which authorized the Truckee-Carson Project. Preexisting dams that raised the level of Lake Tahoe were reconstructed to provide 1.8 m (6 ft) of controllable storage. The newly created Bureau of Reclamation assumed operation of the Tahoe dam in 1913 for irrigation of lands near Fallon, Nevada. The interstate and tribal conflicts created by this project have maintained a steady stream of litigation for eight decades (Jackson and Pisani 1973; Jones 1991; Chisholm 1994). Early in the twentieth century, the state government began considering large-scale water development (Kahrl 1993). A report by the Conservation Commission (1913) devoted half of its 500 pages to water resources. The first comprehensive plan for water development in California was prepared by R. B. Marshall in 1919. A few years later, the California Department of Public Works (1923) released the first statewide hydrographic survey, which examined 1,270 potential reservoir sites and recommended dams at 260 of them. That report led to another comprehensive development plan (Bailey 1927). After California voters approved the concept in 1933 as a state project, California was unable to sell the bonds required for financing. The U.S. Congress stepped in, federalized the proposal, and authorized the Bureau of Reclamation to begin construction of the Central Valley Project in 1935 (Harding 1960; Kelley 1989). Most of the project's water originates outside the Sierra Nevada in the upper Sacramento and Trinity Rivers. The main pieces of the Central Valley Project in the Sierra Nevada, the Friant, Folsom, and New Melones Dams, took decades to complete.

After World War II, other big water projects got under way in the Sierra Nevada, with major dams constructed on the San Joaquin, Kern, Kings, and American before 1960. The big-dam era continued at full speed through the sixties, with projects completed on the San Joaquin, Kaweah, Bear, Mokelumne, Calaveras, American, Merced, Tuolumne, and Yuba Rivers (Kahrl 1978; California Department of Water Resources 1994). The Feather River Project (later named the State Water Project) was approved by the California legislature in 1959 and by the voters in 1960. The centerpiece of the project, Oroville Dam, was completed in 1967.

Although mining in stream channels and water development have been the overwhelming impacts on hydrologic processes in the Sierra Nevada, other human activities in the past 150 years have also altered the hydrology and streams of the range. Unfortunately, there is relatively little information about the extent of these various impacts. We are left, therefore, to a few broad inferences and generalizations.

Grazing

Grazing was perhaps the most ubiquitous impact, as cattle and sheep were driven virtually everywhere in the Sierra Nevada that forage was available (see Menke et al. 1996; Kinney 1996). Anecdotal accounts describe vast herds and severe overgrazing (Sudworth 1900; Leiberg 1902). Overgrazing has been blamed for accelerated erosion beginning in the late 1800s and massive gullying of meadows in the decades that followed (Wagoner 1886; Hughes 1934). Widespread deterioration of meadows led to efforts by the U.S. Forest Service to reduce the degradation (Kraebel and Pillsbury 1934). However, continuing presence of large herds did not allow riparian vegetation to recover enough to reduce erosion of stream banks.

Timber Harvesting

Timber harvesting in the nineteenth century certainly impacted local streams but perhaps mainly because of its typical location: near streams. We can assume that riparian and near-channel forests were targeted during the mining era because they grew on gold-bearing stream deposits and wood was needed where most of the activity was: along streams. Rivers were also used for log transport. As early loggers got farther away from streams, their impacts presumably diminished. Because transportation of the logs was difficult, large amounts of slash were apparently left in the woods. Such material could reduce erosion. In addition, loggers of the 1800s simply lacked the heavy equipment that can grossly disturb hillsides. The advent of railroads had two major impacts on Sierra Nevada forests. Railroad construction consumed vast quantities of lumber for ties, trestles, and snowsheds, and the steam engines burned wood. Railroad logging caused a change in harvesting practices: economics favored removal of almost all trees near the tracks instead of taking individual trees selected for wood quality and relative ease of transportation. Where railway networks allowed large fractions of a watershed to be harvested, local yields of water and sediment could be expected to have increased. Because the degree of ground disturbance from these early logging operations is unknown, their hydrologic effects are difficult to infer. However, because early harvests did not involve road construction and persistent ground skidding to centralized landings, they may be assumed to have had lower impacts than those following World War II.

Wildfire

Fire suppression policies that began early in this century may have caused extensive and persistent changes in the water balance of the forest zone. If forest density significantly increased beyond that generally maintained under a pre-1850 fire regime, then we may assume that evapotranspiration has been maximized in the absence of harvesting. Therefore, the presumably denser forests resulting from fire suppression may have reduced water yields in many basins of the western slope. Quantifying such a reduction is not possible without knowing something about the water relations of forests before the gold rush. Regionally, changes probably do not amount to more than a few centimeters (inches) of areal water depth at most. However, the local effects of denser stands in some instances could be sufficient to reduce the flow of springs and headwater creeks. The thick ground cover resulting from the lack of fires has probably decreased surface erosion as well.

Roads

Following the Second World War, timber production increased markedly, as did construction of forest roads necessary to serve emerging techniques of log removal. The road-building boom of the 1950s through the 1970s was the greatest disturbance of the Sierra Nevada landscape since the gold rush. Initially, forest roads were just built, rather than properly engineered to minimize the risk of mass failure and surface erosion. Stream crossings were particular problems when fords or cull-logs covered with dirt were the preferred means of crossing water. Inadequate road drainage and undersized culverts were common causes of road failure and sediment production. With time, road engineering improved, but total mileage increased as well. At the extreme, up to a tenth of the land area of some catchments became road surface, with a large number of stream crossings.

Point-Source Water Pollution

The first known water pollution by industry other than mining in the Sierra Nevada involved the sawmills near Truckee. Mill waste was disposed of in the nearest de facto sewer, the Truckee River. The large loads of sawdust filled pools in the river, clogged the gravels, and probably removed oxygen from the water, killing fish in the river. Acts of both the California and Nevada legislatures in 1890 and continued enforcement by the California Fish Commission were required to halt the pollution (Pisani 1977). Construction of a pulp and paper mill at Floriston in 1899 added chemical pollutants to the Truckee. This pollution continued until the mill closed for economic reasons in the 1930s (Pisani 1977). Growth of communities in the Sierra Nevada led to water quality problems relating to solid waste and sewage disposal. All known problems were local and relatively minor. Technology for centralized sewage treatment has been both improved and widely deployed throughout the range. Bacteriological water quality around the mining camps may have been poor, as inferred by common intestinal ailments of Euro-American miners that spared the boiled-tea-drinking Chinese laborers (Johnson 1971).

SURFACE WATER QUANTITY

The Sierra Nevada annually yields a large but variable amount of water. Continuous stream-flow records began to be maintained in the mountains less than one hundred years ago and are of short duration with respect to longer-term natural variability. Based on this recent historical record, the Sierra Nevada generates about 25 km^3 (20 million AF) of runoff each year, on average, out of a total for California of about 88 km^3 (71 million AF). Stream flow in the Sierra Nevada is generated by seasonal rainfall and snowmelt. About half of average annual precipitation occurs during winter, about a third in autumn, about 15% in spring, and generally less than 2% in summer (Smith 1982). About 50% of annual precipitation falls as snow at 1,700 m (5,600 ft) at a latitude of 39° N (Kahrl 1978). Stream flow generated below 1,500 m (4,900 ft) is usually directly associated with storms, while stream flow above 2,500 m (8,200 ft) is primarily a product of spring snowmelt. Between these approximate bounds, stream flow is generated both by warmer storms and by melt of snow cover in spring. Of course, the major rivers collect inputs throughout their elevation range with a mix of events. Cayan and Riddle (1993) calculated the seasonal distribution of runoff of six Sierra Nevada rivers (table 30.1), which illustrates that snowmelt runoff becomes more important and midwinter rainfall runoff becomes less important with increasing elevation. In the American River Basin, less than half of annual runoff occurs from April through July in the lower two-thirds of the basin. In small catchments of the American adjoining the Sierra Nevada crest, more than two-thirds of annual runoff occurs during this period (Elliott et al. 1978).

Disposition of Precipitation

Overall, about half the precipitation in the major river basins of the west slope of the Sierra Nevada becomes stream flow (table 30.2) (Kattelmann et al. 1983). Stream flow, both in absolute magnitude and as a proportion of precipitation, increases with elevation. In the American River Basin, streamflow data from twenty-five subbasins (Armstrong and Stidd 1967) indicate an increase in stream flow of about 3 cm per 100 m (3.6 in per 1,000 ft) gain in elevation. Also, in the American River Basin, runoff efficiency increases from about 30% in the foothills to more than 80% near the crest (Elliott et al. 1978). In four small catchments in the Kings River Basin at 1,900 to 2,500 m (6,300 to 8,100 ft), about half the precipitation became stream flow on average. However, there was considerable variation among the nine years of record, depending on total precipitation. Runoff efficiency in the four years with more than 120 cm (47 in) of stream flow ranged from 63% to 75%, while in the five years when stream flow was less than 30 cm (12 in), runoff efficiencies ranged from 21% to 33% (Kattelmann 1989a). A stream gauge on the North Fork of the Kings River at 2,480 m (8,130 ft) is the highest long-term station on the western slope of the Sierra Nevada. This basin of 100 km^2 (39 mi^2) extends above 3,700 m (12,100 ft). The average annual stream flow of 74 cm (29 in) is 70% to 80% of the estimated annual precipitation. About 85% of the annual flow in this basin occurs from April to July (Kattelmann and Berg 1987). In a 1 km^2 (250 acre) research basin in Sequoia National Park at 2,800–3,400 m (9,200–11,100 ft), 75% to 90% of the annual precipitation became stream flow (Kattelmann and Elder 1991). The high-elevation portion of the Sierra Nevada, which covers approximately 3% of California and produces an average of 90 cm (35 in) of annual runoff, contributes about 13% of the state's annual stream flow (Colman 1955). This contribution amounts to an even higher proportion of the state's developed water supply because of its persistence into summer.

TABLE 30.1

Seasonal distribution of stream flow in selected rivers (from Cayan and Riddle 1993).

River Basin	Mean Elevation (m)	Percentage of Mean Annual Stream Flow			
		Aug–Oct	Nov–Jan	Feb–Apr	May–Jul
Cosumnes	1,120	1	21	59	18
American	1,430	2	19	46	33
Stanislaus	1,770	3	13	38	46
San Joaquin	2,290	6	9	29	56
East Carson	2,490	7	11	24	58
Merced	2,740	4	5	21	70

TABLE 30.2

Approximate disposition of precipitation in major rivers (from Kattelmann et al. 1983).

River (Gauging Station)	Precipitation (cm)	Stream Flow (cm)	Losses (cm)
Feather (Lake Oroville)	120	60	60
Yuba (Smartville)	160	100	60
American (Folsom Lake)	135	65	70
Cosumnes (Michigan Bar)	105	35	70
Mokelumne (Pardee Reservoir)	120	65	55
Stanislaus (Melones Reservoir)	115	75	40
Tuolumne (Lake Don Pedro)	110	55	55
Merced (Exchequer Reservoir)	115	45	70
San Joaquin (Millerton Lake)	110	50	60
Kings (Pine Flat Reservoir)	95	50	45
Area weighted average	120	60	60

Snow

Snow plays a dominant role in the overall hydrology of the Sierra Nevada. Storage of frozen precipitation in winter as snow cover and its subsequent release during the spring snowmelt period controls the seasonal distribution of flow in most major rivers. Snow cover is measured at about 400 index locations (300 manually measured snow courses and 100 telemetered snow sensors) in the Sierra Nevada that are used for river forecasting. Basinwide means of April 1 water equivalence for snow courses above 2,500 m (8,200 ft) suggest that peak snowpack water equivalence for the high Sierra Nevada averages 75 to 85 cm (30 to 33 in), decreases from north to south, and is lower on the east side of the crest than on the west side (Kattelmann and Berg 1987). Snow courses between 1,800 m and 2,500 m (5,900 and 8,200 ft) have an average peak water equivalence of about 60 cm (24 in).

Flow Variability

Flow in Sierra Nevada rivers is highly variable in time, both within and between years. Peak flows can be up to five orders of magnitude greater than minimum flows. Annual volumes can be twenty times greater in very wet years than in very dry years. Some smaller streams cease flowing during prolonged dry periods.

Floods

High water levels are an integral feature of Sierra Nevada rivers and have a variety of effects on aquatic biota as well as channel morphology (Erman et al. 1988). Peak flows in the Sierra Nevada result from snowmelt, warm winter storms, summer and early-autumn convective storms, and outbursts from storage (Kattelmann 1990). In rivers with headwaters in the snowpack zone, snowmelt floods occur each spring as periods of sustained high flow, long duration, and large volume. However, they rarely produce the highest instantaneous peaks. The magnitude of a snowmelt flood depends on the spatial distribution of both snow and energy input to the snowpack. The largest volumes occur when all or almost all the basin is contributing high rates of snowmelt runoff. In basins spanning hundreds of meters of elevation with varied aspects, such situations are rare. Snow usually disappears from south-facing slopes and low elevations long before melt rates peak on north aspects and high elevations. Large snowmelt floods occurred in many river basins of the Sierra Nevada during 1906, 1938, 1952, 1969, and 1983. In all cases, snow deposition was more than twice average amounts and persisted into April and May even at low elevations. In basins of less than 100 km^2 (39 mi^2) within the snow zone, maximum specific discharges during snowmelt have ranged from 0.2 to 0.8 m^3 per second per km^2 (18 to 73 ft^3/s/mi^2) on the western slope and 0.1 to 0.2 m^3/s/km^2 (9 to 18 ft^3/s/mi^2) on the eastern slope.

Midwinter rainfall on snow cover has produced all the highest flows in major Sierra Nevada rivers during this century (Kattelmann et al. 1991). The most important factor in rain-on-snow floods is probably their large contributing area. During these warm storms, most of a basin receives rain instead of snow, generating short-term runoff from a much larger proportion of the basin than during cold storms. However, even during the warmest storms, snowpacks above 2,500 m (8,200 ft) rarely melt much because temperatures are close to 0°C (32°F). If snow cover extends to low elevations prior to a warm storm, there can be a substantial snowmelt contribution from those areas. In basins that are largely above 2,000 m (6,600 ft), the highest peaks also tend to be caused by rain-on-snow events. For example, in the Merced River in Yosemite National Park, the four highest floods were caused by rain on snow and were 1.5 to 1.8 times greater than the maximum snowmelt peak of record in 1983. In the past sixty years, six large-magnitude floods (peak flows greater than twice the mean annual flood) have occurred in almost all rivers draining the snow zone: December 1937, November 1950, December 1955, February 1963, December 1964, and February 1986. Specific discharges of these largest floods ranged from 0.2 to 4 m^3/s/km^2 (18 to 360 ft^3/s/mi^2). The largest flood in California history occurred in January 1862. Following hundreds of millimeters (tens of inches) of antecedent rainfall and snowfall down to the floor of the Central Valley, 250 to 400 mm (10 to 16 in) of rain fell in Sacramento (and undoubtedly higher amounts in the Sierra Nevada) between January 9 and 12. High-water marks on the American River near Folsom were 3.5 m (11 ft) above those observed in 1907, the third highest flood measured on the American. In the eastern Sierra Nevada, Owens Lake rose 3 to 4 m (10 to 13 ft) during that winter.

When subtropical air masses move into the Sierra Nevada in summer and early autumn, sufficient moisture is available to generate extreme rainfall. Intense convective storms occurring over a period of three or four days can generate local flooding. These convective storms can generate the greatest floods in some alpine basins that are high enough to avoid midwinter rain-on-snow events. For example, the four highest floods of Bear Creek (gauged near Lake Thomas A. Edison) were generated by summer rainfall. The peak discharge was more than twice that of the largest snowmelt flood in this basin of 136 km^2 (52 mi^2) with a mean elevation of about 2,850 m (9,300 ft). The greatest recorded floods in several east-side streams occurred in late September 1982 when 150 to 200 mm (6 to 8 in) of rain fell in two days.

In limited areas, the greatest floods occur during a sudden outburst from storage because of avalanche-induced displacement of lake water or failure of a natural or man-made dam or aqueduct. Peak flows generated by such mechanisms can be several times greater than those produced by meteorological events.

Droughts

At the other extreme, stream flow in Sierra Nevada rivers can become quite low during intense and/or extended droughts. For example, during 1977 when average snow water equivalence in early April was only 25% of the long-term mean, stream flow as a proportion of average annual flow ranged from 0.08 to 0.26. Basins with most of their area at low elevations generally had the lowest proportions of average volumes. Dry periods may last for several years. From 1928 through 1937, runoff was below average in each year. The past two decades have included record droughts for one year (1977), two years (1976–77), three years (1990–92), and six years (1987–92). The recent six-year drought was similar to the 1929–34 dry period. Total stream flow averaged across many rivers was about half of average in each case (California Department of Water Resources 1994). Other indications of past climate suggest that severe droughts in the Sierra have persisted for periods from decades to more than two centuries (Graumlich 1993; Stine 1994, 1996; Millar 1996; Woolfenden 1996). The presence of tree stumps well below modern lake levels in Lake Tahoe and Lake Tenaya and elsewhere provides strong evidence for very arid conditions in the past (Stine 1994). The period 1937 through 1986 was an anomalously wet period in a 1,000-year-long reconstruction of precipitation from dendrochronological evidence (Graumlich 1993). However, our water resources infrastructure and institutions were largely developed during this period. Inferences about the climate of the past 100,000 years (e.g., Broecker 1995) suggest that great variability in temperature has been common and the temperature of the last 10,000 years was anomalously stable. Any resumption of such a variable climate would be challenging to California's water resource system and society in general. Dramatic shifts in climate could alter the distribution of vegetation over decades to centuries and could interact with a changed precipitation regime to alter runoff generation (Beniston 1994; Melack et al. in press).

Trends

In both extremes of wet and dry conditions, there do not appear to be any strong trends in water becoming more or less available in the recent past. Concern was raised a few years ago that the proportion of annual runoff occurring in the months of April through July in the Sacramento, Feather, Yuba, and American Rivers had declined since about 1910 (Roos 1987). However, this trend appears to be a result of increased runoff for the remainder of the year and no change in absolute amounts during spring (Wahl 1991; Aguado et al. 1992). On the western slope of the Sierra Nevada, there have been no obvious trends in flood magnitude or frequency over the historical period. In rivers of the eastern slope, clusters of events at both extremes have been evident in recent years (Kattelmann 1992). Five of the largest eight to eleven snowmelt floods (in terms of volume) since the 1920s occurred from 1978 to 1986. Five of the smallest thirteen or fourteen snowmelt floods since the 1920s occurred from 1987 to 1991. Instantaneous peak flows have a similar distribution. For example, in Rock Creek, four of the ten largest annual floods and three of the six smallest annual floods occurred during the 1980s. These events support theories of some climatologists that extreme events are becoming more common in the western United States (Granger 1979; Michaelson et al. 1987). Variability in flow remains a defining characteristic of Sierra Nevada rivers.

Even the limited variability in precipitation and runoff that occurred in this century caused water managers to attempt to augment supplies through deliberate weather modification. Soon after the theoretical basis for cloud seeding to increase precipitation was established, the world's first operational program began in the eastern Sierra Nevada in 1948. Within the next few years, cloud seeding programs were started in the San Joaquin, Kings, Mokelumne, and Feather Rivers (Henderson 1995). A dozen programs were active in the Sierra Nevada in 1994 and 1995. Despite dozens of studies, the effectiveness of cloud seeding remains uncertain. Conventional wisdom suggests that a well-designed cloud seeding program may yield up to 6% additional stream flow (American Meteorological Society 1992). Hundreds of papers have been written on environmental effects of cloud seeding (e.g., Berg and Smith 1980; Parsons Engineering Science 1995), but major impacts have not been found, perhaps because of the uncertainty in the amount of precipitation augmentation. The amounts of the primary seeding agent, silver iodide, released in a typical year (7–18 kg [15–40 lb]) over a large river basin are several orders of magnitude less than quantities naturally present in soil.

SURFACE WATER QUALITY

The Sierra Nevada is generally regarded as producing surface water of excellent quality, meaning the water is suitable for almost any use and contains lower amounts of contaminants than specified in state and federal standards. Most of the runoff would be suitable for human consumption except for the risk of pathogens. Very little of the water of the Sierra Nevada can be considered highly polluted (i.e., contaminated with materials having potential adverse effects at concentrations above natural background). Areas of lower water quality correspond to those areas with greater human activities and access. Headwater streams are particularly sensitive to pollution because of low flow conditions and nutrient limitations. The relatively few point sources of pollution throughout the range are mostly associated with inactive mines, dumps, and towns. Many contaminants that enter Sierra Nevada streams can be considered non-point-source pollutants because they are generated over large areas. Livestock waste is an example of non-point-source pollution. Sediment is the most pervasive pollutant because its production may be increased above natural background levels by almost any human activity that disturbs the soil or reduces vegetation cover. Sediment augmented above natural levels usually impairs some beneficial uses of streams. Erosion and sediment are discussed separately in another section of this chapter. Ground-water quality is discussed in the section about ground water. Water temperature is treated in Kondolf et al. 1996.

Human activities in the watershed have the potential to alter nutrient cycling. A classic study in New England provided some of the first measurements of changes in nutrient budgets as a result of complete killing (but not removal) of trees in a small catchment (Likens et al. 1970). This study at Hubbard Brook found that loss of nitrates in stream flow increased by forty times in the first year following devegetation, and export of other nutrients increased several times. Studies in Oregon (Fredriksen 1971; Brown et al. 1973) suggested that typical harvesting procedures that impact less than half of a watershed with deep soils will not significantly contaminate small streams or risk serious declines in soil productivity (Brown 1980). However, frequent harvesting of large portions of catchments with shallow soils and low cation exchange capacity can result in substantial nutrient losses from soils to streams. Elevated concentrations of nitrates and phosphates may be expected in catchments with agriculture, fish farms, and residences. Most of the work on nutrient cycling in the Sierra Nevada has been done in the Lake Tahoe area (e.g., Coats et al. 1976; Coats and Goldman 1993). In one catchment in the Tahoe basin, biological processes effectively prevented release of nitrogen in nitrate form in surface water or ground water (Brown et al. 1990). These authors cautioned that creation of impervious surfaces allows nitrates to bypass potential sinks. Human activities that decrease residence time of water in soils have potential to increase nitrate export. Nitrate concentrations sampled in seventy-seven streams of the eastern Sierra Nevada were less than 1 mg/l in all cases and usually less than 0.1 mg/l, demonstrating that there is usually little export of nitrates in streams (Skau and Brown 1990).

Point-Source Pollutants

There are very few known localized sources of water pollution in the classic outfall-into-the-stream sense in the Sierra Nevada because of the virtual absence of industries that process chemicals and continuing abatement of the few existing sources. Point-source pollution has also been reduced very effectively under the Clean Water Act of 1972 and subsequent amendments. Municipal and industrial discharges are controlled through National Pollutant Discharge Elimination System permits. Most pollution of that general nature is associated with active and abandoned mines and is discussed in the section on mining. Industrial-type pollutants may also be found in the vicinity of many cities and towns and abandoned lumber mills. However, serious problems of this nature are not known to exist (Central Valley Regional Water Pollution Control Board 1957; Central Valley Regional Water Quality Control Board 1991; Lahontan Regional Water Quality Control Board 1993). Over the entire western slope, there are only ten "municipal and industrial discharger groups": Chester, Quincy, Paradise, Portola, Nevada City, Auburn, Placerville, Jackson, Sonora, and Bass Lake (Central Valley Regional Water Quality Control Board 1991). Water quality was considered impaired in streams receiving wastewater from Nevada City, Grass Valley, Placerville, Jackson, and the Columbia-Sonora area (Central Valley Regional Water Quality Control Board 1991).

Sewage

Most communities with a centralized population in the Sierra Nevada have common sewage collection and treatment systems. Discharges from treatment facilities are regulated by the regional water quality control board; however, short-term failures are a persistent difficulty. Disposal of treated wastewaters on land instead of directly into streams is encouraged where practicable (Central Valley Regional Water Quality Control Board 1991). An experiment in Tuolumne County demonstrated several problems with spraying treated effluent on hillsides: the soil became overloaded with nutrients, salts, and water, and algal growth effectively sealed the soil surface, minimizing infiltration (California Division of Forestry 1972). Effluent from a sewage treatment plant in the Lake Tahoe Basin was sprayed over a 40 ha (100 acre) area from 1960 to 1965. Even five years after application ceased, substantial amounts of nitrates were entering a creek downgradient from the site. A stand of Jeffrey pine at the site was also killed by the persistent high level of soil moisture (Perkins et al. 1975).

A significant fraction of the residences in the Sierra Nevada are too dispersed to allow connection to community sewage facilities and rely on individual septic systems (Duane 1996a). Septic systems in Nevada County have led to significant bacteriological contamination in streams below unsewered subdivisions (California Department of Water Resources 1974). Septic tank and leach field systems on individual lots provide a good example of cumulative watershed effects. The soils of a particular catchment have sufficient capacity to treat a particular quantity of sewage under a particular set of conditions. When the soil system is overloaded, some fraction of the waste or its derivatives is discharged to streams. Each residential septic system contributes only a small fraction of the total, but the community as a whole has polluted the catchment. Recreational developments such as ski areas and campgrounds also generate significant quantities of sewage and may have their own treatment facilities if geographically isolated. In the 1950s, Yosemite Valley was the most significant wastewater source in the upper-elevation parts of the San Joaquin River Basin (Central Valley Regional Water Pollution Control Board 1957).

Urban storm water runoff can add a variety of contaminants directly to streams. Pet waste can be a significant source of fecal coliform bacteria in some areas. Street runoff in the Lake Tahoe Basin is beginning to be routed into publicly owned lots to allow for some pollutant removal.

Even in the backcountry, inadequate disposal of human waste from dispersed recreationists has contaminated enough of the streams in remote areas of the Sierra Nevada to make consumption of any untreated water somewhat risky. Although the level of risk is unknown, pathogens including coliform bacteria, campylobacter, and Giardia have been found in many areas throughout the range (Hermann and McGregor 1973; Suk et al. 1986). In a survey of seventy-eight backcountry locations with varying levels of recreational use, Giardia cysts were found in 44% of water samples collected downstream of heavily used areas and 17% of samples from areas of relatively low use (Suk et al. 1987). Giardia cysts have also been detected in fecal matter of cattle grazing in backcountry areas (Suk et al. 1985). Recreational pack stock contribute to nutrient and bacterial pollution. Heavily used trails (e.g., Mt. Whitney) have had sufficient problems with human waste to warrant the installation of backcountry toilets. Low-level release of nutrients from wilderness campers have stimulated increased plant growth on lake bottoms (Taylor and Erman 1979).

Non-Point-Source Pollution

When non-point-source pollution gained widespread recognition as a critical water quality problem in the 1970s, administrative and regulatory approaches were lacking. Eventually, Congress (in the Clean Water Act of 1977 and Water Quality Act of 1987) and the Environmental Protection Agency adopted the concept of best management practices (BMP). This general concept can be stated as doing the best one can to minimize water pollution and meet water quality standards while still conducting the intended activities. Different approaches to developing and applying BMPs have been tried in different states. Ideally, BMPs should reflect the most cost-effective approach to minimizing water pollution in a specific area using practical technology (Dissmeyer 1993; Brown and Binkley 1994). Determining what is most effective and efficient in a particular region should be an iterative process of applying a practice, monitoring its effectiveness, evaluating the cost and impact, modifying the practice in its next application, and so on. Unfortunately, monitoring has been limited, so there is often little basis for improving techniques. However, the learning and refinement process has led to continual improvements in BMPs on national forests in California and on all lands in the Lake Tahoe Basin (U.S. Forest Service 1992; Tahoe Regional Planning Agency 1988). A recent review of forest management impacts on water quality concluded that the use of BMPs in forest operations was generally effective in avoiding significant water quality problems (Brown and Binkley 1994) . However, this report cautioned that proper implementation of BMPs was essential to minimizing non-point-source pollution and that ephemeral channels were often overlooked in the application of BMPs. Additionally, further development work is necessary for BMPs with respect to grazing, maintenance of slope stability, and avoiding losses of nitrates from soils (Brown and Binkley 1994). Much can be done to protect water quality simply by avoiding activities in sensitive areas, such as riparian zones, areas susceptible to mass movement, and areas where soils may become saturated and produce overland flow (Megahan and King 1985). The Tahoe Keys development in a former marsh on the upper Truckee River is an outstanding example of a major failure to respect such areas.

Forest Chemicals

Following the example of agriculture, forest management incorporated the use of fertilizers, pesticides, and herbicides in its operations during the 1960s and 1970s. As concerns about the environmental hazards of such chemicals have grown, their use appears to have decreased (Norris et al. 1991). Even at its peak, the use of silvicultural chemicals was tiny compared with that of agricultural chemicals. On the average, less than 1% of commercial forest land in the United States received any chemical treatment in a year (Newton and Norgren 1977). By contrast, most agricultural land receives multiple treatments every year.

Chemicals have been used in forest management for a variety of purposes (see Helms and Tappeiner 1996). Herbicides limit competition from other species so as to enhance opportunities for conifer regeneration and growth. Herbicide use has declined markedly since the early 1980s, when legal decisions in the Pacific Northwest limited their use and Region 5 of the U.S. Forest Service halted aerial applications of herbicides. However, chemical use now seems to be increasing again under new regulations. The use of insecticides has varied widely between years, depending on insect outbreaks (Norris et al. 1991). Fungicides and soil fumigants can control certain diseases and have been used mostly in tree nurseries. Rodenticides limit damage from gophers and other rodents, and animal repellents have been used to reduce damage to trees from porcupines and rodents. Fertilizers are used to enhance productivity by selectively compensating for nutrient deficiencies (Allen 1987). Fire retardants are the only class of forest chemicals that do not have a parallel in agriculture. They are used at margins of wildfires to slow the rate of fire spread.

Because pesticides, by definition, are toxic to some organisms, they pose hazards to some components of ecosystems. They have long been regarded as a particular threat to water quality and aquatic life (Brown 1980). Their use assumes that managers have decided that the pest that is the object of control efforts really should be eliminated or reduced in number. Therefore, the ecological risk associated with pesticides involves the consequences of that decision and the impacts on nontarget species. In general, the hazard to nontarget organisms depends on the exposure to significant doses and the toxicity of the chemical (Brown 1980). However, some groups of organisms, such as butterflies, are at risk from exposure to certain chemicals (see Shapiro 1996). Toxicological studies of forest chemicals in common use are reviewed by Norris et al. (1991).

Pesticides have the greatest potential to contaminate streams by direct (presumably unintentional) application and wind-borne drift into water courses. Toxicants used in fisheries management are applied intentionally to streams but may have a variety of unintended consequences (see Erman 1996). Spraying by ground crews is much more effective at placing all the pesticide where desired. The greatest potential for pesticides to appear in runoff exists when substantial precipitation occurs soon after the pesticide is applied. Opportunities for a chemical to reach a stream via overland flow depend on the distance from the stream to the closest point of chemical application, infiltration properties of soil and litter, the rate of flow toward the stream, and adsorptive characteristics of soil and organic matter (Brown 1980). Chemicals that reach streams may be removed through volatilization, adsorption on sediments, adsorption by aquatic biota, degradation by chemical, photochemical, or biological processes, and simple dilution with downstream movement (Norris et al. 1991).

Current practice generally limits insecticide and fungicide use to well-defined problems over relatively limited areas, such as insect-outbreak zones and nurseries. By contrast, herbicides can have rather broad application in forestry, and there is public concern about the potential for indiscriminate use. The Record of Decision on the California Region Final Environmental Impact Statement for Vegetation Management and Reforestation (U.S. Forest Service 1988) contains language prohibiting the use of hexazinone and similar herbicides "when they are expected to enter ground water or surface water, such as when soils are very sandy or have low clay or organic matter contents." A letter of October 30, 1990, to forest supervisors from the regional forester suggested that a margin of safety be established so that expected dose levels should be 100 times less than the dose level for which no adverse effects have been detected by laboratory studies. The standard that the Central Valley Regional Water Quality Control Board has established follows EPA practice as 200 parts per billion (ppb) for hexazinone (Stanislaus National Forest 1993). Monitoring for hexazinone in streams has been conducted on the Eldorado National Forest and Sierra National Forest after fall applications between 1991 and 1993. On the Eldorado, fifteen samples out of ninety contained hexazinone ranging from 1 to 19 ppb. No hexazinone has been detected and reported yet on the Sierra National Forest (Stanislaus National Forest 1993). However, a news media account suggested that hexazinone had killed riparian vegetation downstream of an application area on the Sierra National Forest in 1993.

Glyphosphate and triclopyr are two other herbicides that are being used more widely in the Sierra Nevada. Herbicide monitoring programs (Frazier and Carlson 1991) on three national forests in the Sierra Nevada in 1992 and 1993 found trace amounts of the two chemicals in only 3 of more than 120 samples, and those samples testing positive were suspected of being contaminated (Stanislaus National Forest 1993). In studies throughout the United States, chronic entry of herbicides into streams has not been observed (Norris et al. 1991). Artificial alteration of vegetation composition and cover has some potential for alteration of nutrient cycling. We are not aware of research concerning this issue at an operational scale. Pesticides are also widely used in residential areas in the Sierra Nevada and could cause localized contamination.

Fire retardants are applied during crisis situations without the opportunity for careful planning or management. Therefore, their impacts must be considered well before the time they are actually deployed. When aerial application of fire retardants was first used, the main active ingredient was sodium-calcium borate. After a few years, this material was noticed to have a tendency to sterilize the soil and restrict growth of new vegetation following the fire. In recent years, ammonium phosphate and ammonium sulfate have become the primary retardants in active use. Nitrogen in several forms is released as a breakdown product of these chemicals. Nonionized ammonia (NH_3) is the only reaction product that is highly toxic to fish. A series of experiments relating to environmental impacts of ammonium fire retardants found that the compounds had little adverse effect on soil fertility, contributed a short-duration pulse of ammonia to streams, and moderately elevated levels of nitrates in receiving waters (Norris et al. 1978). The quantity of nutrients released by burning is likely to overwhelm any signal of those resulting from retardant application.

Forest chemicals may have a variety of unintended indirect effects on ecosystems by performing more or less as intended but in the wrong places. Insecticides may kill aquatic insects and reduce food supplies for fish. Herbicides can kill aquatic plants and disrupt the food chain at higher levels. Herbicides can also kill riparian vegetation, thereby reducing cover and shade benefits for fish and possibly increasing sediment yields. Death of riparian vegetation can add much organic debris to streams over a relatively short time and possibly deplete dissolved oxygen as it decomposes and also reduce the longer-term supply of organic matter until vegetation is reestablished on the banks. Fertilizers can contribute to eutrophication if the receiving waters are nutrient limited. To restate the obvious, minimizing the adverse impacts of forest chemicals on aquatic ecosystems requires that the chemicals be kept away from the streams and riparian zones.

Atmospheric Deposition

During the 1980s, concerns about the potential effects of atmospherically derived pollutants on aquatic ecosystems (Roth et al. 1985; Schindler 1988) focused attention on high-elevation lakes of the Sierra Nevada (Tonnessen 1984; Melack et al. 1985). The California Air Resources Board initiated a comprehensive study of the sensitivity of a small alpine lake basin in Sequoia National Park as part of a statewide acid-deposition program (Tonnessen 1991). This study explored the hydrochemical processes and biotic responses of this high-elevation system to possible shifts in precipitation chemistry (e.g., Williams and Melack 1991; Kratz et al. 1994). Hydrology and water chemistry of six other high-elevation lakes have been monitored over the past few years (Melack et al. 1993), and deposition has been monitored at several sites (Melack et al. 1995). These studies indicate that the loading rates of hydrogen, sulfate, nitrate, and ammonia are relatively low in the Sierra Nevada compared with rates in other parts of the country. However, snowpack processes can produce a distinct ionic pulse in the early part of the snowmelt season that temporarily lowers the pH of streams and lakes in high-elevation catchments with little buffering capacity (e.g., Williams and Melack 1991). Such surface waters may be at risk of acidification if air pollution and acidic deposition increase (see Cahill et al. 1996). A comprehensive state-of-knowledge review of aquatic impacts of acidic deposition by the University of California at Santa Barbara and the California Air Resources Board should be completed in 1996.

Monitoring

Obtaining adequate knowledge of water quality conditions throughout the Sierra Nevada on a continual basis is challenging at best. Frequent and long-term sampling from dozens to hundreds of sites is necessary to respond to sudden events, detect long-term trends, enforce regulations on discharges, improve the effectiveness of best management practices, and assess overall status. Sampling methodologies and analytical techniques are now fairly well developed (Stednick 1991; MacDonald et al. 1991). Bioassessment techniques using aquatic invertebrates as an integrative index or screening tool of water quality conditions is gaining widespread acceptance (U.S. Environmental Protection Agency 1989). However, broad strategies and philosophies for deciding what parameters to measure in what locations for what purpose have yet to be refined. Interpretation of water quality data to provide a sound basis for management or regulatory actions remains problematic (Ward et al. 1986). Most agencies and individuals concerned with water issues probably find the scarcity of monitoring data frustrating and inadequate to meet their needs. Additions to the present monitoring network will require implementation of creative mechanisms to provide substantial funding. No single agency can accomplish all the necessary monitoring independently. Interagency coordination is needed to maximize efficiency from available funds.

Evaluations of Water Quality in Streams

Assessments of water quality are made by the Department of Water Resources, the Central Valley and Lahontan Regional Water Quality Control Boards, the Environmental Protection Agency, the U.S. Geological Survey, the U.S. Forest Service, reservoir operators and proponents, and various other agencies. Every other year, the State Water Resources Control Board compiles water quality data from the regional water quality control boards and presents its findings to the Environmental Protection Agency under section 305(b) of the federal Clean Water Act. The 1992 Water Quality Assessment listed twenty-one streams draining the west slope of the Sierra Nevada as having serious quality problems. The principal problems in more than half these cases were degradation of fisheries habitat and inadequate flow. Mine drainage was noted in four cases, and sedimentation was recognized as a problem in tributaries of the Feather River and Little Butte Creek. Recreational impacts were mentioned as an additive problem in some cases (California State Water Resources Control Board 1992a). More rigorous criteria were used on the eastern slope, where almost all streams had some impairment of water quality, usually from water diversion or overgrazing. A subset of those streams (Blackwood Creek, Bryant Creek, Carson River, Heavenly Valley Creek, Monitor Creek, and Ward Creek) had more serious problems where violations of water quality objectives had occurred either from sedimentation or mine drainage. A list of thirty streams throughout the Sierra Nevada with various kinds of toxic contamination appeared in a companion report (California State Water Resources Control Board 1992b). Unfortunately, this listing does not rank the problems in terms of severity, and some problems on the list are known to be much more significant than others. What is worse, there is no information available for the majority of streams in the Sierra Nevada.

The Central Valley Basin plan summarizes water quality in Sierra Nevada streams above 300 m (1,000 ft) as "excellent" in terms of mineral content (Central Valley Regional Water Quality Control Board 1991). In general, concentrations increased from east to west (downslope and downstream). The Chowchilla and Fresno Rivers had the highest levels of total dissolved solids among western-slope rivers, but those amounts were still much lower than for streams in the Central Valley. A major assessment of water quality in the Sacramento River Basin was started by the U.S. Geological Survey in 1994 and will continue through 1998.

An evaluation of water quality in ten rivers in the central Sierra Nevada was carried out from 1975 to 1987 (California Department of Water Resources 1989). Nine of the rivers had very low levels of total dissolved solids (less than 150 mg/l—adequate for most industrial applications and well below a state criteria for drinking water of 500 mg/l). The tenth river in the survey, the East Walker, occasionally had high levels of total dissolved solids (up to 800 mg/l). High-elevation lakes in the Sierra Nevada as a group had the lowest ionic concentrations of any region sampled in the United States (Landers et al. 1987).

Several studies have focused on the Truckee River. Because of the high public value of the clarity of Lake Tahoe, water quality in the Lake Tahoe Basin is more thoroughly monitored than that in any other river basin in the Sierra Nevada. Water quality in most of the tributaries to the lake would be considered fine if not for the high sensitivity of the lake to nutrient additions. Downstream of Lake Tahoe, the Truckee River has largely recovered from the intense insults to water quality of the 1870s to 1930s (log transportation on artificial floods, sawdust dumping from lumber mills, and chemical waste from a pulp and paper mill) (Pisani 1977). Today, the principal problem in the Truckee River above Reno is elevated temperature resulting from water storage in Martis Creek, Prosser, Boca, and Stampede Reservoirs (Bender 1994). Total dissolved solids have been in the 6 to 210 mg/l range. Naturally occurring uranium is found in Sagehen Creek, and iron is high in a few places within the Truckee River system (Bender 1994). Water quality problems have been identified on Leviathan/Bryant Creeks (bacteria, nutrients), Little Truckee (nutrients), and Trout Creek (total dissolved solids, suspended sediments) (California State Water Resources Control Board 1984).

Although the surface waters of the Sierra Nevada are no longer pristine in terms of quality or other attributes, most streams could rank as excellent or outstanding compared with conventional standards or water elsewhere in the state, nation, or world. However, water quality in the Sierra Nevada, as elsewhere, is intimately connected to water quantity. Reduction in natural flows because of diversions is perhaps the most widespread water quality problem. Water remaining in the stream must support the same habitat needs and dilute whatever material and heat loads that arrive downstream of the points of diversion. For these reasons, what is usually considered a quantity problem is also a problem of quality. Additionally, there are persistent problems in different river basins. In the Lake Tahoe Basin, nutrient loads that would be considered small anywhere else are accelerating eutrophication of the lake. Within many parts of the Feather River Basin, unstable stream banks resulting from long-term overgrazing and roads are producing sediment yields at the basin scale that are up to four times greater than natural yields. Throughout much of the Sierra Nevada, a few problem mines continue to leach heavy metals into streams, and mercury remains in the beds of many streams from a century ago. Isolated problems such as poorly designed and located septic systems and roads impact local portions of streams and should be correctable by moderate investments for improved water quality.

EROSION AND SEDIMENTATION

Soil erosion, mass wasting, channel erosion, and sedimentation are natural processes that alter the landscape and streams. They are important disturbance mechanisms in terrestrial and aquatic ecosystems. These geomorphic processes are critical in nutrient cycling, transport of organic matter, and creation of fresh surfaces for colonization (Naiman et al. 1992). The rates at which they occur are highly variable across the landscape and over time. These processes operate most intensely in association with major rainstorms and so can be considered episodic in nature. Nevertheless, streams tend to adjust their form to accommodate the long-term sediment supply. Processes that detach and transport particles of soil and rock downslope and downstream can be lumped together as erosion. Sedimentation occurs when these particles come to rest in transitory or long-term storage.

Aquatic Effects

Alteration of stream sediments can seriously impact populations of fish and other aquatic organisms. Aquatic ecosystems have developed in response to a particular regime of water and sediment flows and channel conditions. When conditions change, such as when annual floods cease because of a dam or the proportion of silt-size sediments increases because of a road built next to the stream, some organisms will benefit and some will suffer. Trout and other salmonids require streambed deposits of gravel-size particles in which to prepare nests (redds) for their eggs where there is substantial flow of water and dissolved oxygen. Until the fry emerge after two to six months, the redds are vulnerable to scour and deposition of other sediments that could block flow of water through the redd (Lisle 1989). When sediment inputs to a stream exceed the transport capacity of the channel, fine sediments (clays, silts, and sands) tend to accumulate on the bed surface (Lisle and Hilton 1992). Fine sediments have been found to fill substantial fractions of pools in streams on the Sierra National Forest that were known to have high sediment yields, such as Miami Creek (Hagberg 1993). These fine sediments often smother invertebrates, reduce permeability of streambed gravels and fish-egg nests (redds), impede emergence of fish fry, and cause poor health or mortality of fry at emergence because of reduced levels of dissolved oxygen (Burns 1970). Sedimentation also adversely impacts invertebrate habitat (Erman 1995). In many streams in the Sierra Nevada, suitable gravels for spawning are found only in isolated pockets and lower-gradient reaches (Kondolf et al. 1991; Barta et al. 1994). The limited extent of such areas increases their importance for fisheries maintenance. Fortunately, scour and deposition processes are highly variable within and between streams, so that some spawning areas are almost always available (Lisle 1989). Sediment transport processes in streams of the Sierra Nevada have been the subject of few studies (e.g., Andrews and Erman 1986), and even basic information is scarce. Much of the sediment in mountain streams consists of large particles known as bedload. In fourteen streams of the eastern Sierra Nevada, the proportion of bedload varied between 0% and 65% of the total sediment load (Skau et al. 1980).

Natural Sediment Yields

Natural surface erosion is generally regarded as small in the Sierra Nevada because of high infiltration capacity of the soils, predominance of snowmelt as a water input to soils, rarity of overland flow, predominance of subsurface flow, and relatively continuous vegetation cover. The sources and pathways of sediments supplied to stream channels are not completely understood. The channel system itself is an obvious candidate as a source for most of the sediment (King 1993). During persistent rainfall and peak snowmelt, the network of very small channels becomes rather extensive, mobilizing sediment from a large fraction of a watershed. Such sediment probably does not move very far but may be made available for transport by a high-magnitude runoff event. The sequence of events of different magnitudes can determine the net sediment transport over long time periods (Beven 1981). In the Sierra Nevada, the greatest potential for overland flow to occur appears to be below the snow zone in woodland-grassland communities between 300 and 900 m (1,000 and 3,000 ft) (Helley 1966). The maximum rates of sediment production have been observed in this same altitude range (Janda 1966). The woodland zone also was the primary sediment source in part of the American River Basin with annual erosion of about 150 m^3/km^2 (0.3 AF/mi^2) (Soil Conservation Service 1979).

Accelerated Erosion

Human activities often disrupt the natural geomorphic processes and accelerate erosion or destabilize hill slopes. Modeling erosion in the Camp and Clear Creek Basins suggests that disturbance, especially roads, can increase erosion many times above natural rates (McGurk et al. 1996). When soil loss and sediment transport occur at unusually high rates in response to some human disturbance, erosion and sedimentation become issues of concern. Accelerated soil loss is primarily a problem in terms of losing productivity for growing vegetation (Poff 1996). Excessive sedimentation can damage terrestrial plants and aquatic organisms. High levels of sediment deposition can also reduce the utility of facilities for water storage and diversion and hydroelectric production. At the extreme, hydraulic mining for gold on the west slope of the Sierra Nevada intentionally eroded entire hillsides. The resulting sedimentation in downstream river channels left deposits tens of meters thick. Sediment yield in the Yuba River was up to twenty-five times greater than natural rates (Gilbert 1917) and led to a legal decision effectively halting hydraulic mining. Activities that purposefully move soil, such as construction of roads and structures, have the greatest potential for increasing erosion. Activities that reduce vegetative cover and root strength can also increase erosion rates. Activities in and near stream channels have the greatest potential for altering sediment delivery and storage as well as channel form. For example, destruction of riparian vegetation can lead to massive streambank erosion, or dams can trap sediment from upstream while causing channel incision or narrowing downstream.

Processes involving movement of large units of soil or rock rather than individual particles are collectively known as mass wasting. Landslide activity is a typical mass failure in which a portion of a slope fails all at once. Movement may be catastrophic in seconds or progressive over years. Mass wasting may be important in providing a material supply to channels slowly through soil creep or suddenly when a debris flow reaches a stream, but it is not regarded as a major erosive agent in most of the Sierra Nevada (Seidelman et al. 1986). Mass movement typically occurs when most of the pores in the material become filled with water. The positive pressure of the pore water and its added mass may exceed the strength of the material, and failure of part of the slope may occur. Unusually high rates of water input to previously wet soils can lead to large numbers of landslides in the Sierra Nevada (De Graff et al. 1984). Disturbance of slopes accelerates the natural occurrence of landslides (Sidle et al. 1985). Excavations across slopes for roads intercept water flowing downslope through the soil and increase pore water pressure at the exposed seepage face. In granitic portions of the Sierra Nevada, ground-water flow is often at a maximum at the interface between the porous coarse-grained soils and underlying relatively impermeable bedrock (De Graff 1985). Exposure of this layer can bring large quantities of water to the surface (Seidelman et al. 1986). Such excavations also reduce the mechanical support for adjacent parts of the slope. Tree roots are often important in maintaining the integrity of a slope. Minimum strength occurs about ten years after fire or timber harvesting when roots from young trees have not yet compensated for the progressive loss of old roots (Ziemer 1981). Most opportunities to minimize mass wasting as a consequence of road construction and forest harvesting involve commonsense approaches to avoiding accumulation of subsurface water on steep slopes (Sidle 1980; McCashion and Rice 1983).

In years of high precipitation with large individual storms, the number, extent, and size of mass movements increase well above those of years with modest precipitation. Landslides were particularly active during the wet years of 1982 and 1983. In both those years, springs and seeps appeared in places they had not been noticed before, including many road cuts and fills. More than $2 million in damage occurred to roads on national forests in the Sierra Nevada during 1982, and additional damage estimated at more than $1 million occurred in 1983 (De Graff 1987). A landslide in the American River canyon blocked U.S. 50 for April, May, and June of 1983. Sustained high levels of soil moisture and ground water occurred throughout the winter and spring of each year. Additional water input from rainfall, combined rainfall and snowmelt, and snowmelt alone triggered the unusual number of failures (Bergman 1987; De Graff 1987). However, there seems to be relatively little interaction between high flows and initiation of landslides within the inner gorges of Sierra Nevada streams (Seidelman et al. 1986). Landslides can also be initiated by earthquakes (Harp et al. 1984) and summer thunderstorms (Glancy 1969). An extraordinarily intense storm occurred in the headwaters of the South Fork of the American River on June 18, 1982 (Kuehn 1987). About 100 mm (4 in) of rain fell in 30 minutes and produced a peak flow of about 200 $m^3/s/km^2$ (19,000 $ft^3/s/mi^2$). These values of precipitation intensity and specific runoff are records for the Sierra Nevada and well above values assumed to be the maximum possible in the range (Kuehn 1987). The event also caused a large debris torrent in a small basin that had been burned the previous year.

Roads

Roads are considered the principal cause of accelerated erosion in forests throughout the western United States (California Division of Soil Conservation 1971a; California Division of Forestry 1972; Reid and Dunne 1984; McCashion and Rice 1983; Furniss et al. 1991; Harr and Nichols 1993). Roads destroy all vegetation and surface organic matter, minimize infiltration and maximize overland flow, oversteepen adjacent cut-and-fill slopes to compensate for the flat roadbed, and intercept subsurface flow, directing more water across the compacted surface (Megahan 1992). Stream crossings by roads are particularly effective at increasing sediment yields because of their direct impact on the channel. Stream banks are excavated for bridges and filled for culverts. Failure of inadequately designed and constructed culverts adds large amounts of sediment to streams. Increases in fine sediment and decreases in fish populations were associated with the number of culverts and roads near streams on the Medicine Bow National Forest in Wyoming (Eaglin and Hubert 1993). A classic study in the granitic batholith of Idaho found that sediment yields relative to an undisturbed forest increased by 60% as a result of logging and by 220 times (22,000%) from road construction (Megahan and Kidd 1972). A compilation of studies in the Oregon Coast Range showed that the quantity of mass movements associated with roads was 30 to 300 times greater than in undisturbed forest and was more than 10 times greater than that associated with large clear-cuts (Sidle et al. 1985). Large highway projects also produce significant amounts of sediment, with fill slopes often providing the most easily transported material (Howell et al. 1979). During major storms, highways are often damaged and provide much sediment to streams. For example, during February 1986, four serious debris flows in the Truckee River canyon closed Interstate 80, and sixty-three road failures occurred along 55 km (35 miles) of the Feather River Highway 70 (McCauley 1986; Keller and King 1986).

Land Development

Construction activities also have the potential to increase erosion rates (California Division of Soil Conservation 1971a). Residential construction around Lake Tahoe has been a major contributing factor in accelerating erosion and increasing nutrient inputs to the lake (Tahoe Regional Planning Agency 1988). In Nevada County, even by 1970, more than 35% of the length of streams in the county had been damaged by siltation and stream-bank erosion resulting from subdivision development (Gerstung 1970). Only a few examples of major erosion are well documented. For example, erosion from a single storm on freshly cleared land for a new subdivision in Plumas County killed 80% of the aquatic life in Big Grizzly Creek (California Division of Soil Conservation 1971b). Sediment from a failure of a channelization project for a new golf course largely filled Hunter's Reservoir on Mill Creek (California Division of Soil Conservation 1971b).

Logging

Timber harvesting itself seems to have relatively little effect on soil erosion compared with the construction of roads used for log removal (see McGurk et al. 1996; Poff 1996). Although soil disturbance associated with cutting trees and skidding logs exposes mineral soil to raindrop splash as well as to rill development where soils are compacted, in practice, comparatively little soil leaves harvested areas. The California Division of Forestry (1972) has asserted that "timber harvesting, when done carefully with provisions made for future crops, has little adverse effect upon soil erosion, sedimentation, or water quality." During his evaluation of sedimentation from hydraulic mining, Gilbert (1917) noted that erosional effects of timber harvesting were minor compared to other, nonmining effects such as overgrazing and roads. Several factors appear to mitigate potential adverse effects of harvesting: only small and discontinuous areas are compacted to an appreciable extent; infiltration capacity is generally maintained over large areas; a lot of slash is left behind; and some type of vegetation usually reoccupies the cutover land quickly. Another important factor to date has been the concentration of harvests in the most productive sites and most accessible areas, which tend to be on relatively gentle slopes. As harvesting moves to less desirable and steeper ground, risk of erosion and mass failure will increase. Avoidance of lands sensitive to disturbance, such as slopes greater than 60%, streams with soil-covered inner gorges, riparian areas, meadows, and known landslides, will minimize erosion associated with timber harvest (Seidelman et al. 1986).

Despite mitigating factors that can reduce logging-related erosion, some harvest units lose large amounts of soil. Such areas appear to be a minority, although their local effects can be quite significant. The degree of soil compaction seems to be a controlling influence on subsequent erosion (Adams and Froehlich 1981). Severe sedimentation in the West Fork of the Chowchilla was noted after upstream areas were virtually denuded of vegetation to supply fuel for a smelter at the Mariposa Mine about 1900 (Helley 1966). The headwaters of Last Chance Creek on the Plumas National Forest had erosion rates from 150 to more than 300 m^3/km^2 (0.15 to 0.66 AF/mi^2) during a severe thunderstorm following a salvage sale in the Clark Fire area (Cawley 1991). A series of studies of northern California streams, including some in the Sierra Nevada, found significantly greater amounts of fine sediments and altered benthic invertebrate communities downstream of logged slopes (Erman et al. 1977; Newbold et al. 1980; Erman and Mahoney 1983; Mahoney and Erman 1984). Some effects of logging on streams were persistent for more than a decade (Erman and Mahoney 1983; O'Connor 1986; Fong 1991). A study of erosion rates from small plots recently started by Robert Powers of the Redding office of the Pacific Southwest Research Station of the U.S. Forest Service should improve our understanding of erosion processes and rates in the Sierra Nevada.

Christmas tree plantations have been found to have very high rates of erosion (Soil Conservation Service 1979). Management for Christmas trees typically attempts to minimize other ground cover that would compete for water and, therefore, makes the plantations more vulnerable to erosion.

Measured Sediment Yields

Compared to other parts of California and the United States, the Sierra Nevada overall has relatively low sediment yields (Brown and Thorp 1947). A map of soil erodibility for California shows the absence of "very severe" ratings throughout the Sierra Nevada except for areas of western Plumas and eastern Butte Counties and in part of Yuba County, whereas such ratings are common in the Coast Range (California Division of Soil Conservation 1971a). General estimates shown on another statewide map show that the Sierra Nevada has the lowest sediment yield in California (generally less than 100 $m^3/km^2/yr$ [0.2 $AF/mi^2/yr$]) (California Division of Forestry 1972). Sediment transport measurements in a variety of streams in the eastern Sierra Nevada were generally less than 10 m^3/km^2 (0.02 AF/mi^2), but there were exceptions of up to 450 m^3/km^2 (0.9 AF/mi^2) (Skau and Brown 1990). An estimate of annual sediment yield for the San Joaquin Basin above the San Joaquin valley based on a comprehensive geological investigation was about 38 m^3/km^2 (0.08 AF/mi^2) (Janda 1966). For comparison, an average value for the entire United States is 76 m^3/km^2 (0.16 AF/mi^2) (Schumm 1963). The Colorado River Basin produces about 300 $m^3/km^2/yr$ (0.6 $AF/mi^2/yr$) and the Columbia River yields about 30 $m^3/km^2/yr$ (0.06 $AF/mi^2/yr$) (Holeman 1968). A compilation of sediment studies from forested regions provided an average rate of about 30 $m^3/km^2/yr$ (0.06 $AF/mi^2/yr$) from forest land in the United States excluding the Pacific Coast Ranges (Patric et al. 1984). A Soil Conservation Service report classified sediment yields below 150 m^3/km^2 as "low" with respect to nationwide rates (Terrell and Perfetti 1989).

The best means of determining sediment yields over long time periods is with repeated bathimetric surveys of reservoirs (Dunne and Leopold 1978; Hewlett 1982; Rausch and Heinemann 1984). Comparison of the bottom topography after a span of a few years allows calculation of the change in volume of sediment over the time interval (Rausch and Heinemann 1984; Jobson 1985; Mahmood 1987). Most of the information for the Sierra Nevada came from a Soil Conservation Service study in the 1940s (Brown and Thorp 1947). This same data set has been republished many times (e.g., Dendy and Champion 1978; U.S. Army Corps of Engineers 1990; Kondolf and Matthews 1993), but there have been few additions to it. Until 1975, the Committee on Sedimentation of the Water Resources Council compiled data for reservoir surveys throughout the United States (Dendy and Champion 1978). Records of suspended sediment at water quality monitoring stations reported by the U.S. Geological Survey were also examined but did not prove to be useful. Almost all stations are downstream of dams, and uncertainty resulting from the assumptions required to estimate annual totals would mask any trends over time.

Estimates of average annual sediment yields in the Sierra Nevada were compiled from all available sources (tables 30.3 and 30.4). These values provide order-of-magnitude approximations of sediment yield. The numbers should be considered uncertain and may contain some serious errors resulting from the original measurements, assumption of inappropriate densities if reported as mass rather than volume, and conversion from some unusual units. The period of measurement varies greatly between basins, resulting in different sediment delivery regimes depending on the inclusion of floods. Some of the values in tables 30.3 and 30.4 were based on total basin area above the reservoir or measurement site, and others were based only on the sediment contributing area not regulated by upstream reservoirs and lakes. Tables 30.3 and 30.4 illustrate that sediment yields vary considerably between river basins but that the generalizations mentioned above seem appropriate. Most reported values are less than 100 $m^3/km^2/yr$ (0.2 $AF/mi^2/yr$), which is the simple average of table 30.4. This value can be visualized as a tenth of a millimeter in depth over the entire contributing area, which is not how sediment is produced, but the conversion is useful for illustration. The relatively high sediment yields of the Kaweah and Tule are somewhat surprising, especially in the Kaweah Basin, which is largely in Sequoia National Park. However, this short period (1960–67) includes the massive floods of February 1963 and December 1964, which would tend to bias the annual sedimentation rate.

Unfortunately, very few measurements of reservoir sedimentation have been reported in the past two decades. The one-time measurements in isolation do not provide sufficient information or provide much confidence in using the values to infer differences between basins or over time. Comparison of modern sedimentation rates with those summarized by Brown and Thorp (1947) would be very useful in determining whether more intensive land management has altered sediment yields at the basin scale. A highly detailed bathimetric survey of Slab Creek Reservoir (in South Fork American River Basin) in 1993 revealed less than 0.5 m of accumulation on the bed of the reservoir since 1968 but did not estimate the volume of the deposit (Sea Surveyor, Inc. 1993). Crude estimates based on information provided in the report suggest an annual sediment yield less than 10 m^3/km^2 (0.02 AF/mi^2).

TABLE 30.3

Sediment yields from reservoir surveys.

Site	Drainage Area (km^2)	Elevation of Dam (m)	Interval (years)	Annual Sediment Yield (m^3/km^2)	Annual Sediment Yield (AF/mi^2)	Source
Sacramento Tributaries						
Magalia	21	681	18–46	150	0.3	Brown and Thorp 1947
Yuba						
Bullards Bar	1,226	488	19–39	130	0.2	Brown and Thorp 1947
Bear						
Combie	330	488	28–35	360	0.8	Brown and Thorp 1947
American						
Ralston	1,095	362	66–89	80	0.2	EA 1990
Folsom	6,955	146	55–91	250	0.5	California Department of Water Resources 1992 in Kondolf and Matthews 1993
Cosumnes						
Big Canyon	14	232	34–45	30	0.1	Brown and Thorp 1947
Blodgett	8	48	40–45	80	0.2	Brown and Thorp 1947
Calaveras						
Davis	19	34	17–45	120	0.3	Brown and Thorp 1947
Gilmore	13	69	17–45	60	0.1	Brown and Thorp 1947
McCarty	1	350	37–45	140	0.3	Brown and Thorp 1947
Salt Spring Valley	47	357	82–45	100	0.2	Brown and Thorp 1947
Stanislaus						
Copperopolis	5	297	15–45	20	0.03	Brown and Thorp 1947
Lyons	102	1,287	30–46	50	0.1	Brown and Thorp 1947
Mokelumne						
Pardee	980	173	29–43	70	0.2	Brown and Thorp 1947
Pardee	980	173	29–95	150	0.3	EBMUD 1995
Upper Bear	72	1,791	00–46	10	0.2	Brown and Thorp 1947
Schadd's	72	886	40–90?	100	0.2	Euphrat 1992
Tuolumne						
Don Pedro	2,550	186	23–46	100	0.2	Brown and Thorp 1947
La Grange	3,842	92	95–05	40	0.1	Brown and Thorp 1947
Merced						
Exchequer	2,616	216	26–46	80	0.2	Brown and Thorp 1947
San Joaquin						
Crane Valley	135	1,026	01–46	80	0.2	Brown and Thorp 1947
Kerckhoff	3,031	296	20–39	80	0.2	Brown and Thorp 1947
Mammoth Pool	2,550	1,026	59–72	90	0.2	Anderson 1974
Kings						
Hume	62	1,616	09–46	10	0.03	Brown and Thorp 1947
Pine Flat	3,948	296	54–56	90	0.2	Dendy and Champion 1978
Pine Flat	3,948	296	54–56	30	0.1	Anderson 1974
Pine Flat	3,948	296	56–73	80	0.2	Dendy and Champion 1978
Wishon	445	2,000	58–71	10	0.03	Anderson 1974
Kaweah						
Terminus	1,453	212	61–67	360	0.8	Dendy and Champion 1978
Tule						
Success	1,006	190	60–67	400	0.9	Dendy and Champion 1978
Kern						
Isabella	5,309	776	53–56	35	0.1	Dendy and Champion 1978
Isabella	5,309	776	56–68	90	0.2	Dendy and Champion 1978
Walker						
Weber	6,241	1,284	35–39	10	0.02	Dendy and Champion 1978
Weber	6,241	1,284	?	30	0.05	Soil Conservation Service 1984

TABLE 30.4

Sediment yields from suspended sediment records and other estimates.

Site	Drainage Area (km^2)	Annual Sediment Yield (m^3/km^2)	Annual Sediment Yield (AF/mi^2)	Source
Feather				
Oroville	9,244	90	0.2	Jansen 1956
Oroville	9,244	100	0.2	U.S. Army Corps of Engineers 1990
Oroville	9,244	120	0.3	Soil Conservation Service 1989
East Branch North Fork	3,131	270	0.6	Soil Conservation Service 1989
Yuba				
Nonmining		160	0.3	Gilbert 1917
Hydraulic mining		3,300	7	Gilbert 1917
Castle Creek	10	70	0.1	Anderson 1979
Castle Creek (logged)	10	220	0.5	Anderson 1979
American				
Auburn dam site	2,485	130	0.3	U.S. Army Corps of Engineers 1990
Cameron Park		70	0.2	Soil Conservation Service 1985
Onion Creek	4	30	0.06	Dendy and Champion 1978
Cosumnes				
Michigan Bar	1,098	30	0.06	Anderson 1979
Stanislaus				
New Melones	2,314	60	0.1	U.S. Army Corps of Engineers 1990
Merced				
Happy Isles	463	3	0.01	Anderson 1979
Chowchilla				
Buchanan		40	0.1	Helley 1966
San Joaquin				
Kerckhoff		40	0.1	Janda 1966
Kings				
Teakettle	7	10	0.02	Dendy and Champion 1978
Kern				
????	2,613	150	0.3	Anderson 1979
Truckee				
Tahoe Basin	839	30–60	0.05–0.1	Tahoe Regional Planning Agency 1988
Tahoe (in 1850)	839	3	0.01	Tahoe Regional Planning Agency 1988
Upper Truckee	142	21	0.04	Hill and Nolan 1990
General Creek	19	13	0.03	Hill and Nolan 1990
Blackwood Creek	29	65	0.14	Hill and Nolan 1990
Ward Creek	25	63	0.13	Hill and Nolan 1990
Snow Creek	11	3	0.005	Hill and Nolan 1990
Third Creek	16	20	0.04	Hill and Nolan 1990
Trout Creek	95	12	0.03	Hill and Nolan 1990
Squaw Creek	21	12, 93	0.03, 0.2	Woyshner and Hecht 1989
Sagehen	28	2	0.005	Anderson 1979

Recent bathimetric surveys of Pardee Reservoir on the Mokelumne River suggest that the average annual rate of sediment deposition has more than doubled since the last survey in 1943 (150 m^3/km^2 [0.3 AF/mi^2]) (EBMUD 1995). Parts of the Mokelumne River Basin have been extensively roaded and logged in the past few decades, and there has been much concern about apparent increases in sediment yield from some of the erodible soils (e.g., Euphrat 1992). These new results offer evidence of a sedimentation response to large-scale disturbance of a forested basin. Much greater sedimentation rates are apparent in Camanche Reservoir, downstream of Pardee. Additional studies are needed to determine the sources of sediment trapped in Camanche. At rates of deposition suggested by the recent sediment surveys, half the original storage volume of Camanche would be lost in 380 years, and half of the original storage volume of Pardee would be lost in 600 years.

An Example of Disturbance Effects

The North Fork Feather River has perhaps the worst erosion and sediment problem of any large basin in the Sierra Nevada. Conditions were certainly much worse in several drainages during the hydraulic mining era and for following decades until most of the debris was flushed into the lower reaches of the river systems. Nevertheless, sediment production under current conditions in the North Fork Feather River can be considered high compared with natural background rates (Plumas National Forest 1988). A comprehensive evaluation of sediment sources in the basin found that about 90% of the erosion and about 80% of the sediment yield is accelerated (induced by human activities) (Soil Conservation Service 1989). That estimate and the current sediment yield of about 270 m^3/km^2 (0.6 AF/mi^2) imply that under natural conditions, sediment yield would be about 50 m^3/km^2 (0.1 AF/mi^2). The difference is caused mainly by bank erosion where riparian vegetation has been eliminated by overgrazing and erosion from road cut-and-fill slopes (Soil Conservation Service 1989; Clifton 1992, 1994). Mining, logging, and overgrazing before 1900 initiated widespread changes in hydrologic conditions of the land surface and channels. Gullying and channel erosion were noted by the 1930s (Hughes 1934). After about 1940, stream channels widened rapidly with little reestablishment of riparian vegetation along new channel banks. More than 75% of the stream length in the Spanish Creek and Last Chance Creek watersheds was found to be unstable and eroding (Clifton 1992). Bank erosion contributes sediment directly into the streams, which in turn transport it to lower elevations. About one-third of the forest roads are eroding rapidly as well and often contribute sediment directly into streams where roads cross or run parallel (Clifton 1992). By contrast, sheet and rill erosion appear to produce very little (less than 2% of the total) of the sediment in the basin because the nearly continuous vegetation cover protects the soil (Soil Conservation Service 1989). A cooperative effort among local landowners, public agencies, Pacific Gas and Electric Company, and private individuals is attempting to reduce erosion throughout the basin (Wills and Sheehan 1994; Clifton 1994). The Pacific Gas and Electric Company is involved because it operates two small reservoirs in the canyon of the North Fork Feather River as part of its hydroelectric network. Sediment is rapidly filling the reservoirs, interfering with operation of the control gates on the dams and accelerating turbine wear (Harrison 1992). A costly program of dredging and reconstruction of the dams to allow pass-through sluicing of sediment during high flows is being planned in addition to participation in the upstream erosion control program (Pacific Gas and Electric Company 1994). A few other reservoirs in the Sierra Nevada have filled with sediment and had to be dredged. This topic is discussed further in the section on dams and diversions.

GROUND WATER

Ground-water storage is generally limited throughout the Sierra Nevada compared with surface water resources. However, ground water is significant in providing small amounts of high-quality water for widely scattered uses, such as rural residences and businesses, campgrounds, and livestock watering. Without ground water, the pattern of rural development in the Sierra Nevada would be quite different. The geology of the mountain range is not conducive to storage of large quantities of subsurface water. Ground water occurs in four general settings: large alluvial valleys; small deposits of alluvium, colluvium, and glacial till; porous geologic formations; and fractured rocks. The shallow aquifers tend to be highly responsive to recharge and withdrawals. The effects of low precipitation in the recent drought cannot be readily separated from effects of increased pumping on declining water levels in some areas. Tens of thousands of wells tap ground water throughout the Sierra Nevada for local and distant municipal supply, individual residences, and recreational developments. Nearly one-quarter of all homes in the Sierra Nevada are supplied by private, on-site wells (Duane 1996a). More than 8,000 residents of Tuolumne County alone depend on wells for water supply. In 1982, there were about 5,800 wells in Placer County, 6,100 in El Dorado County, 3,400 in Amador County, and 2,200 in Calaveras County (California Department of Water Resources 1983a). Some of these wells were west of the SNEP study area. Contamination appears to be minimal overall (California State Water Resources Control Board 1992a).

Ground-Water Resources

A few ground-water basins in the Sierra Nevada store vast quantities of water, but they have limited recharge compared with some proposed exploitation plans. Honey Lake/Long Valley has a capacity of about 20 billion m^3 (16 million AF) in alluvial and lake sediments up to 230 m (750 ft) thick. The quality is poor in some areas, with high concentrations of boron, fluoride, sulfate, sodium, arsenic, and iron. Sierra Valley stores about 9 billion m^3 (7.5 million AF) of water in sediments up to 370 m (1,200 ft) deep. Hot springs occur in the center and southern part of the valley, and excessive amounts of boron, fluoride, and chloride have been found in some wells. Several schemes have been proposed for mining ground water from both Sierra Valley and Long Valley for export to Reno. Martis Valley contains about 1 billion m^3 (1 million AF) of water, is an important water source for the Truckee area, and has the lowest concentration of total dissolved solids (60–140 mg/l) of any large ground-water basin in the state. By contrast, ground water in the 4 billion m^3 (3.4 million AF) volume Mono basin is highly mineralized. The Owens Valley is the largest ground-water basin partially within the SNEP study area, with a storage capacity of about 47 billion m^3 (38 million AF). Export of ground water from the Owens Valley to southern California began in 1970. This ground-water development led to declines of ground water dependent vegetation (e.g., Groeneveld and Or 1994) and continues (as of 1995) to be the subject of negotiations between Inyo County and the City of Los Angeles. Smaller alluvial valleys include Indian and American Valleys of the Feather River Basin, Tahoe Valley in the upper Truckee River Basin, Slinkard and Bridgeport Valleys of the Walker River Basin, and Long Valley in the Owens River Basin.

Many wells in the Sierra Nevada are located in shallow deposits of glacial till, alluvium, and colluvium. These surficial deposits, which are often only a few tens of meters deep (Page et al. 1984; Akers 1986), are fairly porous and convey water to streams. Deeper deposits are capable of serving the needs of small communities but may be sensitive to recharge conditions. Placer County (1994) has determined that ground water in the foothills is not a reliable source of water for future growth.

Some rocks and other geologic formations, like buried river channels, are relatively porous and transmissive. Hydrogeologic properties of these formations are highly variable, as are well yields. Locating a well is often hit-or-miss, but drillers familiar with an area can usually find sources of water adequate for residential use. Mixed results have been obtained in recent drilling through the complex layers of till, volcanic ash, and basalt found in the Mammoth Lakes area. Some wells have been highly productive, and others have quickly gone dry.

Granitic and metamorphic rocks of the Sierra Nevada are essentially impermeable except where fractured. In some locations, the joint and fracture systems can transmit significant quantities of water. A recent study in the Wawona area of Yosemite National Park investigated fracture systems and the regional movement of deep ground water (Borchers et al. 1993). Most wells in southwestern Nevada County, and presumably in other parts of the foothills with similar geology, are located in areas of fractured rock (Page et al. 1984). Of some 13,000 wells drilled in Placer, El Dorado, Amador, and Calaveras Counties between 1960 and 1982, more than 90% were located in hard rock (California Department of Water Resources 1983). The size and frequency of fractures decline with depth away from the surface, so the more productive wells in Nevada County have been less than 60 m (200 ft) deep. Mean yield in that study area was less than 70 l/min (18 gal/min) (Page et al. 1984), with about half the wells yielding less than 38 l/min (10 gal/min) (California Department of Water Resources 1974). Average well yields determined from drillers' logs were less than 80 l/min (20 gal/min) in both Nevada and Amador Counties (Harland Bartholomew and Associates et al. 1992; California Department of Water Resources 1990a). Wells in Tuolumne County are often more than 90 m (300 ft) deep and are adequate for domestic use. The drought between 1987 and 1992 limited recharge throughout the Sierra Nevada, and yields of many wells declined through the period. There is insufficient information available to determine whether the proliferation of wells throughout the foothills in the past decade has had a pronounced effect on preexisting wells.

Pumping of water for industrial uses has lowered water tables in western Tuolumne County (comments by Tuolumne Utility District in DEIS on Yosemite Estates). Ground-water pumping can also impact local stream flow. Interactions between ground water and streams are very complex in some areas of the Sierra Nevada where glacial till is interlayered with volcanic mudflows and ash and is dissected by old stream courses and faults (Kondolf and Vorster 1992). Drilling of supplemental water-supply wells for Mammoth Lakes raised concerns that pumping could further reduce flows in Mammoth Creek, which is already diverted as the principal water source for the town (Kattelmann and Dawson 1994).

In a small lake basin in the alpine zone of Sequoia National Park, water released from short-term subsurface storage accounted for less than 15% of the annual stream-flow volume, but it controlled the chemistry of stream and lake water for more than two-thirds of the year (Kattelmann 1989b).

Springs are an important water source for small demands that require minimal development. Because springs are often fed by shallow aquifers, they are more susceptible to contamination than deep sources and often require protection of their contributing areas. Dense vegetation resulting from decades of fire suppression may maximize transpiration losses from hill slopes above springs, thereby reducing spring flow. Developing springs as a water source usually alters or even eliminates riparian and aquatic habitat in the immediate area. Springs are one of the most threatened habitats in the Sierra Nevada (see Erman 1996). Springs as well as pumped water are commercially developed for packaging as mineral water. Bottled water operations are present in the northern and southern Owens Valley.

Ground-Water Quality

The mineral content of ground water is generally much higher than that of surface water. The long residence time of water in the ground allows it to dissolve minerals and accumulate ions. Nevertheless, total dissolved solids in ground water in the Sierra Nevada are usually not an impediment for use. Deeper ground water in parts of the Honey Lake/Long Valley Basin and the Mono basin and below Mammoth Lakes contain substantial concentrations of various ions. Concentrations of naturally occurring iron are sometimes too high for domestic uses (Thornton 1992; Placer County 1994). Some wells in Kern Valley have very high levels of fluoride. Shallow ground water may be contaminated with nutrients from septic and sewage disposal systems, livestock, and chemicals applied to farms and gardens. Nutrients found in ground water in the Lake Tahoe Basin were relatively low in an absolute sense, but they still contributed to enrichment of the lake waters (Loeb and Goldman 1979). Water quality problems of the larger ground-water basins in the Sierra Nevada identified in the biennial state water quality assessment included drinking water impairment from heavy metals, fuel leaks, volatile organic compounds, naturally occurring radioactivity, pesticides, and wastewater (California State Water Resources Control Board 1992a). Some wells in the foothills of the southern west slope of the Sierra Nevada have been found to contain concentrations of uranium, radon, and radium above state health standards (California Department of Water Resources 1990b). Water in certain hot springs has high levels of natural radioisotopes. High levels of radionuclides have also been found in wells of the Lake Tahoe Basin (California Department of Water Resources 1994).

The leaking underground storage tank problem has probably introduced fuels to ground water in isolated spots throughout the Sierra Nevada. Gasoline contamination has been documented in Bishop, Mammoth Lakes, Bridgeport, and Placer County. Tetrachloroethylene, a solvent used in dry cleaning, was found in two municipal wells in East Sonora. The wells were removed from service, and an expensive extension to surface water supply was installed. Old landfills are another potential source of contamination.

MINING

Historically, mining had the most intense impact on rivers of the Sierra Nevada. As discussed in the history section, hydraulic mining for gold until 1884 truly wreaked havoc throughout the Gold Country. Affected streams and hill slopes have been recovering ever since. In most cases, the degree of recovery is remarkable. Much of the region appears to have healed over the past century. In terms of their more obvious hydrologic and biologic characteristics, the streams have improved dramatically compared to photographs and descriptions of the nineteenth century. Stream channels are now largely free of mining sediment, although large deposits remain as terraces (James 1988). Riparian vegetation has become reestablished. Aquatic biota have returned to the streams, at least partially. Some fish species that would be expected are not present in rivers heavily impacted by mining (Gard 1994). We can assume that the present form of the ecosystems is simplified compared to the pre–gold rush situation, but we really do not know what the west slope of the Sierra Nevada might have looked like had gold not existed in the range. Unfortunately, the Gold Country was so heavily mined that “natural” streams are not available for comparison. Portions of streams that were lightly impacted could be compared to those that were heavily impacted, but doubt would remain about what constitutes “natural” conditions. The water projects initiated during the mining period and other associated land uses have further modified the hydrologic system.

Legacy of Hydraulic Mining

After the 1884 Sawyer decision and the 1893 Caminetti Act, hydraulic mining continued on only a sporadic basis where the debris could be kept on-site. Mines in three old hydraulic pits in the Yuba River Basin were active in the late 1960s: near French Corral, Birchville, and North Columbia (Yeend 1974). A few such mines continue operation today. When the original mines closed, there was no attempt at site reclamation, and the mines were simply abandoned. A variety of dams were constructed in attempts to prevent further movement of mining debris downstream (Rollins 1931). Only the larger, better-engineered structures did not fail. Dams such as Combie on the Bear, Englebright on the Yuba, and North Fork on the American have restrained vast amounts of mining debris from washing downstream to the Sacramento valley. An attempt to destroy a debris dam on Slate Creek with explosives was made in the 1960s by miners desiring another opportunity to recover gold. The initial bombing failed, but the structure is damaged and loses sediment during floods (Kondolf and Matthews 1993). Also along Slate Creek, a wooden wall retaining a large volume of mining debris appeared ready to fail in 1994. The hydraulic mine pits are slowly becoming revegetated, but they continue to release unnaturally high volumes of sediment as their walls continue to collapse until a stable slope angle is attained (Senter 1987). The unnaturally high sediment loads continue to affect aquatic biota (Marchetti 1994). A large open-pit gold mine that was operated at Jamestown until 1994 offers the first major opportunity for modern reclamation technology to be applied to a recently closed mine in the Sierra Nevada. The pit may also be used as a garbage dump. Current mineral potentials are discussed in Diggles et al. 1996.

Dredging

Massive riverbed dredging operations at the lower margins of the foothills persisted until 1967 (Clark 1970). The spoil piles may remain as a peculiar landscape feature for centuries. Some of the tailings in the Feather River were used in construction of the Oroville Dam, and other uses of the material and the land may be found. Small-scale suction dredging continues in many streams of the Gold Country. This activity has become widespread wherever there is easy access to the streams (McCleneghan and Johnson 1983). Powerful vacuums mounted on rafts remove stream gravels from the bed for separation of any gold particles, and the waste slurry is returned to the river, where the plume of sediment stratifies in the flowing stream. Turbidity obviously increases, and the structure of the bed is rearranged. The morphology of small tributaries can be dramatically altered by suction dredging (Harvey 1986; Harvey et al. 1995). Where stream banks are illegally excavated, the potential for damage is much greater. A study of effects of suction dredging on benthic macroinvertebrates showed local declines in abundances and species richness, but biota rapidly recolonized the disturbed sites after dredging stopped (Harvey 1986). Although dredging seems to have relatively little impact on adult fish, eggs and yolk-sac fry and amphibians within the gravel are usually killed by dredging (Johnston 1994). Dredging also has the potential to reintroduce mercury stored in sediments contaminated by early mining (Harvey et al. 1995; Slotten et al. 1995).

Underground Mining

Hard-rock mining often releases hazardous materials to ground water and streams. The nature and impacts of some of the typical mine effluents are reviewed by Nelson et al. (1991). Excavation of hard-rock mines exposes tunnel walls and tailings to water and oxygen and vastly increases the reactive surface area of minerals, allowing chemical reactions to occur at much faster rates than if undisturbed. If the mines or their waste piles contain sulfide minerals, oxidation in the flowing water can release sulfuric acid and metals into the drainage water. Exposure as a result of mining also allows reaction products to be leached from tailings piles or abandoned mines. Contaminated water can be flushed into streams in sudden pulses during storm runoff or slowly during base flow. In some cases, these products are highly toxic, and the runoff is acidic. The downstream extent of impacts along streams seems to depend on interactions between source concentrations, hydrologic characteristics of the mine or waste rock, storm characteristics, chemical behavior of the particular constituents, bacterial influences, presence of other substances as complexing agents, and dilution potential of the receiving waters. Fortunately, the mineralogy and geochemistry of most mines in the Sierra Nevada have resulted in relatively few serious surface-water problems (Montoya and Pan 1992). However, exceptions such as the Leviathan, Walker, and Penn mines have seriously degraded downstream areas. The substrate of a housing development built on tailings of the Central Eureka mine near Sutter Creek contains arsenic levels about seventy-five times greater than average values for soils in California. Discharge from mine dewatering and from rejuvenation of closed mines probably released toxic materials into nearby streams. Abandoned pits often fill with water and attract waterfowl and other wildlife. If the water contains toxic materials, these substances can enter the food chain.

Water Quality Impacts

An inventory of mines causing water quality problems has been developed by the Central Valley Regional Water Quality Control Board (1975). Mines in the Sierra Nevada included on that list appear in table 30.5. All except two are underground mines. The list is evenly split between gold mines and mines for other minerals, chiefly copper.

A more recent survey by the Central Valley Regional Water Quality Control Board (Montoya and Pan 1992) limited to the Sacramento valley investigated thirty-nine inactive mines from Butte Creek to the American River. Water quality of the drainage from these mines and waste piles was highly variable between mines and over time. For example, copper concentrations below the Spenceville mine on Dry Creek southwest of Grass Valley were up to eight times higher than EPA standards in the first hours of a rainfall-runoff event and then decreased with time. Such sudden spikes in concentrations may be harmful to aquatic life but are rarely captured in water quality sampling. Many of the adits of the different mines were dry when visited and were not releasing contaminants. Most of the mines studied in the Yuba River Basin were releasing high levels of arsenic because the gold in this region is associated with arsenopyrite minerals. Otherwise, mine runoff in this area was typically clear and was not acidic. Gold mines in the Bear River Basin were similar to those in the Yuba, but copper mines had acidic discharge with high levels of copper, zinc, cadmium, and other metals. Mines in the lower American River Basin near Folsom Lake were dry and did not appear to have serious water quality problems. The study demonstrated that surface-water quality problems associated with mines are highly site specific. Insufficient ground-water monitoring has been done in the vicinity of mines in the Sierra Nevada to identify potential problems.

The amount of mercury used in gold extraction in the Sierra Nevada and largely lost to soils and streams has been estimated at 3.4 million kg (7.6 million lb) (Central Valley Regional Water Quality Control Board 1987). Mercury is known to exist in streams below gold-ore processing sites; however, the bioavailability of mercury in the Sierra Nevada is not well understood. A survey found elevated concentrations of mercury in the upper tributaries of the Yuba, Bear, Middle Fork Feather, and North Fork Cosumnes Rivers

TABLE 30.5

Mines cited by the Central Valley Regional Water Quality Control Board (1975) as degrading local water quality.

Mine	Receiving Stream
Cherokee	Sawmill Ravine / Dry Creek / Butte Creek
Mineral Slide	Little Butte Creek / Butte Creek
China Gulch	Lights Creek / Wolf Creek / North Fork Feather River
Engel	Lights Creek / Wolf Creek / North Fork Feather River
Iron Dyke	Taylor Creek / Indian Creek / Wolf Creek / North Fork Feather River
Walker	Little Grizzly Creek / Indian Creek / Wolf Creek / North Fork Feather River
Kenton	Kanska Creek / Middle Yuba River
Malakoff Diggings	Humbug Creek / North Fork Yuba River
Plumbago	Buckeye Ravine / Middle Yuba River
Sixteen to One	Kanska Creek / Middle Yuba River
Dairy Farm	Camp Far West Reservoir / Bear River
Lava Cap–Banner	Little Clipper Creek / Greenhorn Creek / Rollins Reservoir / Bear River
Alhambra Shumway	Rock Creek / South Fork American River
Copper Hill	Cosumnes River
Newton	Copper Creek / Sutter Creek / Dry Creek / Mokelumne River
Argonaut	Jackson Creek / Dry Creek /Mokelumne River
Penn	Mokelumne River
Empire	Copper Creek / Black Creek / Tulloch Reservoir / Stanislaus River
Keystone	Penny Creek / Sawmill Creek / Black Creek / Tulloch Reservoir / Stanislaus River

(Slotten et al. 1995). The heavy metal is readily trapped in reservoir sediments, and lower concentrations have been measured below reservoirs than above (Slotten et al. 1995). Mercury concentrations exceeded 0.5 mg/kg in sediment samples obtained from Camp Far West Reservoir, Lake Wildwood, Lake Amador, and Moccasin Reservoir (Central Valley Regional Water Quality Control Board 1987). Certain bacteria can convert metallic mercury to a methylated form that can be incorporated in tissue. Mercury tends to accumulate in the food chain. Although the opportunity for bacterial mercury methylation is minimized in cold, swift streams, the process can occur in the calm waters of reservoirs (Slotten et al. 1995). However, the reservoirs do not appear to be net exporters of bioavailable mercury. Instead, they seem to be sinks for both bioavailable and inorganic mercury (Slotten et al. 1995). Tissue samples of fish caught in the Yuba River contained more than 1 mg/kg, and samples exceeding 0.5 mg/kg were found in fish caught in Pardee, Don Pedro, and McClure Reservoirs (Central Valley Regional Water Quality Control Board 1987). A National Academy of Sciences report suggests that mercury amounts in tissue exceeding 0.5 mg/kg may be injurious to animals.

The Penn mine near the lower Mokelumne River has been considered one of the worst abandoned-mine problems in the Sierra Nevada. The mine was opened in 1861 and operated continuously until 1919 and then sporadically until the 1950s. Copper and zinc were the primary products of the mine (Heyl et al. 1948). More than 16,000 m (55,000 ft) of tunnels and the associated spoil provide the opportunity for percolating ground water to become acidic and leach zinc, copper, and cadmium from the mine. Flushing of some of the mine shafts in 1937 killed fish for 100 km (60 mi) downstream. A series of retention ponds were constructed and other attempts were made to restrict movement of the contaminants into the river in the 1980s, but they have had limited effectiveness (California State Lands Commission 1993). Until 1929, water draining from the mine into the Mokelumne River was diluted by the large volume of discharge. However, after the construction of Pardee Dam by the East Bay Municipal Utility District and export of up to one-third of the annual volume of the river upstream of the mine, concentrations of contaminants in the Mokelumne increased (Slotten et al. 1994). The dam for Camanche Reservoir just downstream of the mine was completed in 1964. Toxic materials leached from the mine are stored in sediments trapped by the dam. The potential for resuspension of the metals is minimal as long as water levels are kept relatively high (Slotten et al. 1994). In December 1993, the Environmental Protection Agency ordered the East Bay Municipal Utility District to control pollution from the mine. However, the utility contends that it is not responsible for the mine, which was last operated by the federal government during the Korean War.

The Leviathan mine provides another example of a water quality problem resulting from an abandoned operation. A copper and sulfur mine on Leviathan Creek in the Carson River Basin near Monitor Pass was started by the Anaconda Copper Company in 1953. Overburden was dumped in the stream channel, causing the water to percolate through the material. Below the stream blockage, the water is highly acidic and polluted with toxic materials. The stream was sterile below the mine during the 1950s. In 1969, an isolated population of rainbow trout still existed in the unpolluted portion of Leviathan Creek above the mine. Below the mine, fish and macroinvertebrates were absent from 18 km (11 mi) of stream affected by the mine drainage. The effects of the pollution even extend for 3 km (2 mi) in the East Fork of the Carson River below the confluence with the contaminated creek (Davis 1969; Hammermeister and Walmsley 1985). Attempts at revegetating the spoils began in the 1970s (Everett et al. 1980).

Reclamation

California's Surface Mining and Reclamation Act of 1975 and amendments should prevent future disasters (Pomby 1987), but remediation of past problems requires massive investments. Even ascertaining the location of abandoned mines remains problematic (Desmarais 1977). Sealing of much of the Walker mine, a notorious problem in Plumas County, in 1987 significantly lowered copper concentrations in receiving waters and allowed partial recolonization of formerly sterile reaches by macroinvertebrates (Bastin et al. 1992). There is also a major question of liability in cleanup efforts. Current law holds those attempting remediation to be liable for any damage caused by their activities or, presumably, failure of the project to solve the problem. Therefore, under the cloud of legal liability, little action is undertaken by private or public agencies (California State Lands Commission 1993). Scores of small mines have been established under the terms of the antiquated 1872 Mining Act. In many cases, the properties are sources of sediment and toxic chemicals. Reform of portions of the Mining Act could finally alleviate some major land and water management problems associated with mining. Conversely, legislation has been introduced in California to weaken the state's regulations regarding reclamation of mined land.

Future Prospects

Changes in mineral economics and technology and new discoveries may lead to new mines. Reactivation of a large underground gold mine near Grass Valley has been proposed. Water pumped out of that mine would probably require thorough treatment before it could be discharged. In the eastern Sierra Nevada, the tungsten mine in Mt. Morgan on Pine Creek has been maintained on a standby basis awaiting an increase in the price of the metal. Reactivation of gold mines at Bodie and Independence Creek have been explored in recent years. A disseminated gold deposit in Long Valley near Mammoth Lakes has been identified through exploratory drilling in

1989–94. About one part per million of the ore is gold, which could be recovered through massive excavation and cyanide heap-leach processing.

Aggregate Mining

Sand and gravel are the most economically important nonfuel minerals mined in California. The $560 million value of sand and gravel produced in California in 1992 far surpassed the combined total value of all metallic minerals mined in the state (McWilliams and Goldman 1994). More aggregate is used per capita in California than in any other state, and the State Department of Transportation is the largest single consumer (California State Lands Commission 1993). Because aggregates are fundamental to most types of modern construction, they are used in almost every building and roadway project. The widespread demand and high transport costs of sand and gravel make aggregate production a highly dispersed mining activity (Poulin et al. 1994). Each 40 km (25 mi) of transport doubles the cost as delivered (California State Lands Commission 1993), so sources near the construction site are highly desirable. Materials excavated from stream deposits tend to be durable and have relatively few impurities and, therefore, are favored over hill slope deposits (Bull and Scott 1974).

Excavation within stream channels will obviously have direct effects on the fluvial system (Sandecki 1989; Kondolf and Matthews 1993). Removal of part of the streambed alters the hydraulic characteristics of the channel and interrupts the natural transport of bedload through the stream. The most immediate consequence is degradation of the bed both upstream and downstream. Creation of a hole in the streambed makes the channel locally steeper and thereby increases the shear stress on the bed. Erosion of the bed will propagate upstream as additional sections become steeper and erode progressively (Collins and Dunne 1990). The initial pit also serves as a bedload trap and relieves the stream of part of its load. The flowing water will then have greater availability to erode the bed in the downstream direction (Kondolf and Matthews 1993). The downcutting reduces the proportion of smaller sediments and can produce a bed composed of cobbles and boulders. Some stream reaches can lose their deposits of gravels that are suitable for fish spawning. The deeper channel can lower the local water table and kill riparian vegetation as the former floodplain dries out. Loss of the vegetation in turn makes the banks more susceptible to erosion. Incision of the channel limits the opportunity for overbank flooding to deposit sediments on the floodplain. These combined effects can result in dramatic changes in the overall form and structure of the channel and dependent aquatic and riparian habitat (Collins and Dunne 1990; Kondolf and Matthews 1993). Human structures in the channel such as bridges, culverts, pipelines, and revetments may be damaged by the geomorphic changes.

Gravel is also mined from streams by skimming a shallow layer off of gravel bars. Depending on the flow regime, distribution of particle sizes, and opportunities for establishment of riparian vegetation, a variety of complex channel and vegetation responses may occur (Kondolf and Matthews 1993). Mining of terrace deposits and abandoned channels can be problematic if the channel shifts enough to reoccupy the excavated areas. A swiftly flowing stream can be converted into a series of giant ponds if the floodplain and terraces are extensively excavated and then captured by the stream. Part of the lower Merced River suffered such a conversion in 1986 with serious impacts on a salmon population (California State Lands Commission 1993). Abandoned gravel pits and quarries well above the stream channel can also act as major sources of sediment input to streams (California Division of Soil Conservation 1971a).

The number and location of in-stream gravel operations in the Sierra Nevada is unknown, but large mines have been identified on the East Branch of the North Fork of the Feather, Middle Feather, North Yuba, Yuba near Camp Far West Reservoir, Bear, lower American, and Calaveras below New Hogan Dam (California State Lands Commission 1993). A major gravel mine operating on Blackwood Creek in the Tahoe basin increased sediment yield from the watershed about fourfold (Todd 1990). Smaller operations are assumed to be widespread throughout the Sierra Nevada. Reservoir deltas appear to be an environmentally benign source of aggregate, and removal would extend reservoir capacity. The delta of the Combie Reservoir on the Bear River has been mined for sand and gravel since 1946 (Dupras and Chevreaux 1984). Mining has occurred on the delta of Rollins Reservoir upstream from Combie (James 1988). Gold was recovered from sand and gravel operations during the construction of Friant Dam on the San Joaquin River in 1940–42 (Clark 1970).

Geothermal Resources

Geothermal energy is another subsurface resource that has potential adverse impacts on water resources when developed. Heat can be extracted from portions of the earth's crust that are unusually warm and close to the surface by pumping out hot water and using its heat to vaporize another fluid that drives turbines, which generate electricity. During the 1970s, many parts of the Sierra Nevada were explored for geothermal potential. Monache Meadows on the Kern Plateau was proposed for large-scale development. Geothermal energy in the Sierra Nevada has been developed most extensively in Long Valley near Mammoth Lakes. The large complex of geothermal power plants, located at Casa Diablo near the junction of Highways 395 and 203, had a capacity of more than 30 megawatts in 1991. The power plants operate as a completely closed system, reinjecting the water after some of its heat has been removed. After several years of operation, changes in nearby hot springs have been observed, and effects are suspected but not proven at springs feeding a fish hatchery downgradient. Additional geothermal development is being considered near Casa Diablo, Mono Craters, and Bridgeport Valley in Mono County.

DAMS AND DIVERSIONS

Impounding and diverting of streams are the principal impacts on the hydrologic system of the Sierra Nevada. While other resource management activities cause environmental alterations that, in turn, may affect stream flow, water management activities avoid the intermediate steps and intentionally and directly alter the hydrologic regime. The thoroughness of the hydraulic engineering in the Sierra Nevada that has been developed over a century and a half is probably underestimated by most water users in California. However, one simple fact stands out: no rivers reach the valley floor unaltered. Only three Sierra Nevada rivers greater than 65 km (40 mi) long flow freely without a major dam or diversion: Clavey, Middle Fork Cosumnes, and South Fork Merced Rivers (figures 30.2–30.4). Selected segments of the North Fork American, Middle Fork Feather, Kern, Kings, Merced, and Tuolumne Rivers receive some protection from additional dams under the National Wild and Scenic River System (Palmer 1993). Few streams get very far from their source before meeting some kind of structure. In the Mono Lake and Owens River Basins, about 730 km (460 mi) out of 850 km (530 mi) of streams are affected by water diversions (Inyo National Forest 1987). In California's Mediterranean climate, water is most available in winter and spring. Dams are built to reduce the peak flows of winter, provide irrigation water during the growing season, provide domestic and industrial water on a semiconstant basis, allow optimum hydroelectric generation, and secure some interannual storage for protection against drought. With so many uses of water, attempts to manage it are found throughout the Sierra Nevada.

Structures

The total number of water management structures in the Sierra Nevada is unknown but must be in the thousands. The storage capacity of all dams in the range is about 28 billion m^3 (23 million AF), which is about the average annual stream flow produced in the range. The dozen largest reservoirs (each with capacity greater than 500 million m^3 [400,000 AF]) account for about three-fourths of the rangewide storage capacity. The smallest dams in the Sierra Nevada are those built for minor domestic water supply on small creeks and may impound only a few cubic meters of water. Somewhat larger dams have augmented natural lakes and were often built for fisheries management purposes. Most of these dams were constructed before World War II, but a few continued to be built up to the 1960s. Their main purpose was to store water for releases in late summer to maintain some stream flow for fish survival. About thirty such dams were built on the Eldorado National Forest (1980).

Dams are constructed in a great range of sizes for various purposes. Dams of a few meters' height are found throughout the Sierra Nevada to improve hydraulic conditions for tunnel intakes diverting water for municipal supply or irrigation or toward powerhouses. Such dams or weirs are not intended to have any effect on the seasonal pattern of stream flow. Dozens of small dams for small-scale hydroelectric production were proposed throughout the Sierra Nevada under the favorable climate created by the Public Utility Regulatory Policy Act of 1978 (California Energy Commission 1981). Many of these projects were ill conceived and were based on unrealistically high projections of future energy prices. Only a small proportion of those proposed were ever built. Several existing and proposed hydroelectric projects are being reconsidered by their owners or proponents because of currently low prices for electricity. The larger diversion dams can store stream flow accumulated over a few days. Dams intended to redistribute water over time have storage capacities equivalent to the stream flow of at least several weeks. A few of the megaprojects can hold more water than is produced in an average year. These massive structures account for most of the storage in an entire river basin. For example, the New Melones Reservoir has 84% of the total storage capacity in the Stanislaus River Basin, while the next largest forty dams in the basin represent only the remaining 16% (Kondolf and Matthews 1993). The dam at Lake Tahoe controls only 1.8 m (6 ft) of storage, but the vast area of the lake makes its storage volume the ninth largest in the Sierra Nevada. The big dams in the Sierra Nevada cause many of the same problems as other large dams in the western United States (e.g., Hagan and Roberts 1973). These dams prevent the further migration of anadromous fish and completely change the water and sediment regimes downstream. The combined effects of all the large dams on rivers tributary to the Sacramento River have significantly modified the annual hydrograph of the largest river in the state (Shelton 1994).

The other critical structures in water management are the conduits and canals for transferring water between rivers or to powerhouses or users. The vast network of artificial waterways redistributes water over short and long distances. A water molecule can take a very circuitous journey from the mountainside to the valley through several pieces of the plumbing system. Many of the old ditches and canals originally constructed during the mining era and that still supply water for hydroelectric generation, municipal use, or irrigation have become a secondary channel system. They both collect water from and discharge water to soils and slopes. In a 160 km (100 mi) long canal network in El Dorado County, about half of the initial water plus any gains en route are lost to seepage (Soil Conservation Service 1984). Water-supply agencies have sought to increase the efficiency of their antique delivery systems by reducing seepage from the old ditches. Replacement of the open ditches with pipes avoids

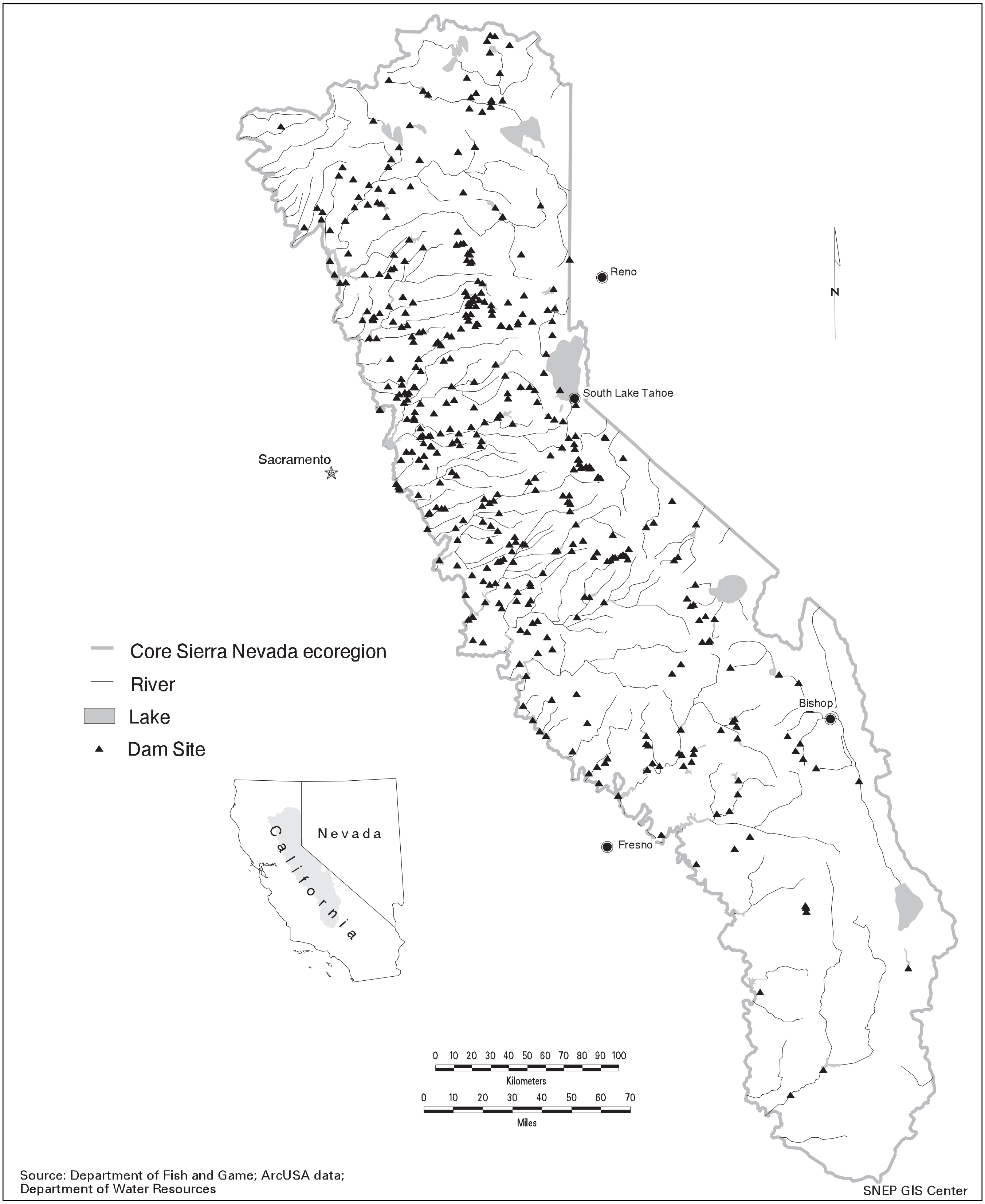


FIGURE 30.4

Larger dams that are regulated by the California Division of Dam Safety are found on almost all major streams of the Sierra Nevada.

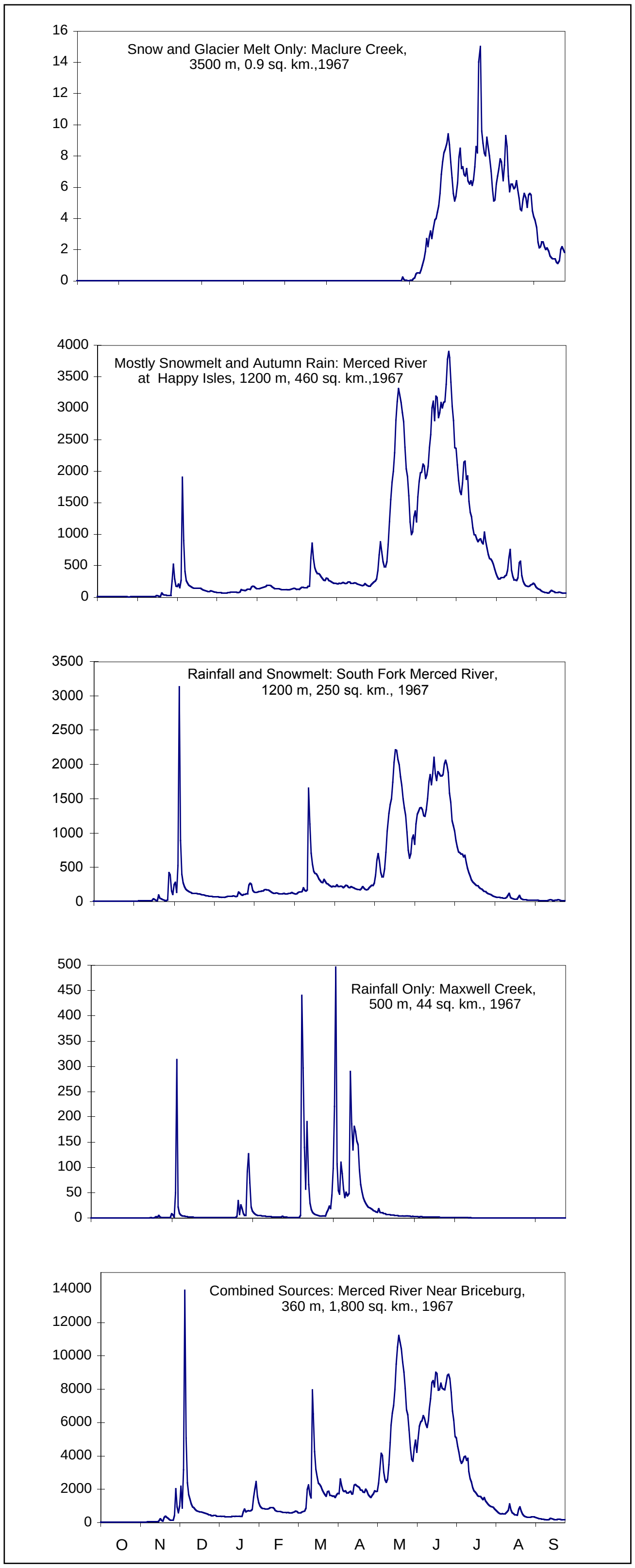


FIGURE 30.5

Watersheds with different elevation ranges and sources of runoff have different patterns of stream flow over a water year (October to September).

contamination of the enclosed water and provides greater operational flexibility. However, a finding by the staff of the State Water Resources Control Board held that improvements effectively constitute a new diversion that the ditch owner does not hold rights to. Leakage currently provides water for improvement of wildlife habitat and other uses. A decision is pending on this case involving the Crawford Ditch of the El Dorado Irrigation District (Borcalli and Associates 1993). Occasional failures of these (and more modern) canals result in serious erosion or debris flows. Four flume failures occurred along the Tule River just between 1962 and 1965. In 1992, the Cleveland fire in the South Fork of the American River Basin destroyed a large portion of the El Dorado Canal, which supplies about a third of the total water to the El Dorado Irrigation District. In November 1994, a fallen oak blocked the Tiger Creek Canal, diverting water to the slope below and eroding hundreds of cubic meters of soil.

Environmental Consequences

The construction, existence, and operation of dams and diversions have a variety of environmental effects. Inundation of a section of stream is the most basic impact. A river is transformed into a lake. The continuity of riverine and riparian habitat is interrupted. To creatures that migrate along such corridors, this fragmentation has consequences ranging from altering behavior of individuals to devastating populations. Dams have the potential to alters downstream flows by orders of magnitude and, at the extreme, can simply turn off the water and dry up a channel. Changing the natural transport of water and sediment fundamentally alters conditions for aquatic and riparian species. Changing stream flow also has dramatic impacts on chemical and thermal attributes of downstream water. The abundance of impoundments in the Sierra Nevada is impressive when one realizes that virtually all flat water at the lower elevations of the west slope is manmade. The terrain is simply not conducive to the formation of natural lakes below about 1,500 m (5,000 ft).

An obvious impact of water management is alteration of the natural hydrograph (temporal pattern of stream flow). For example, during the snowmelt season, the daily cycle of runoff and recession may be transformed into a constant flow. A series of hydrographs from streams in and near Yosemite National Park illustrate natural stream flow patterns generated under various watershed and climatic conditions at different elevations (figure 30.5). Dams are built to change those patterns (figure 30.6). Diversions not associated with large impoundments change the volume without much effect on timing (figure 30.7). Large projects usually alter both volume and timing (figure 30.8).

High Flows

The most obvious alterations in formerly natural hydrographs are decreases in peak flows. The size of an impoundment and

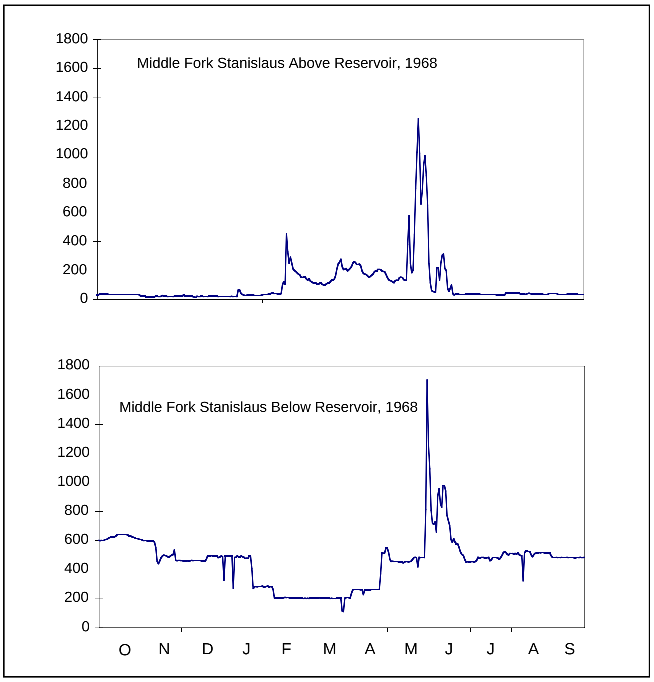


FIGURE 30.6

Storage reservoirs without diversions can greatly modify the natural hydrograph without reducing the annual volume.

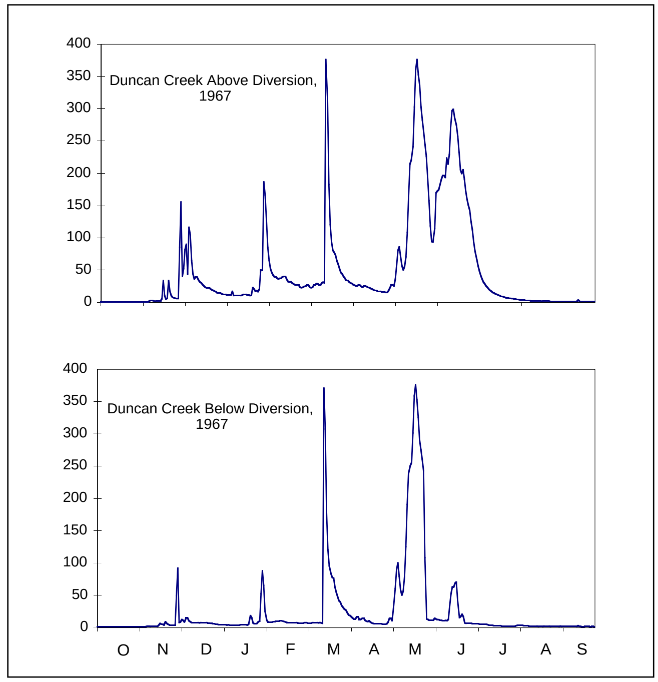
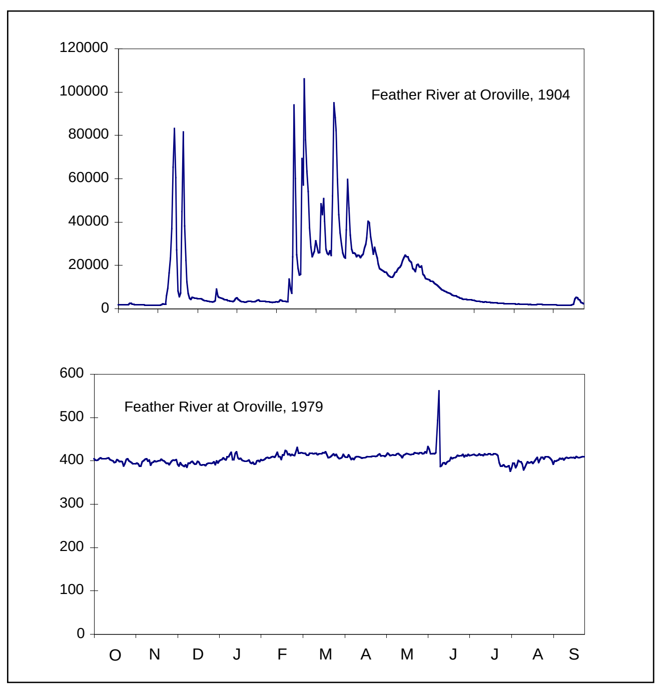


FIGURE 30.7

Diversions at small dams with minimal storage reduce the volume of stream flow without eliminating the natural pattern of fluctuations.

FIGURE 30.8

The largest reservoirs and associated diversions completely change the availability of water downstream. Note the extreme difference in scale (thousands of cubic meters per second in 1904 versus a constant 11 m^3/sec in 1979) after the Oroville Dam was completed.



its flood reservation (management rules to keep a portion of the reservoir unfilled depending on the risk of floods at different times of the year) determine its ability to capture floodwaters and release them at a controlled rate. Small structures must pass the bulk of a flood without much influence. Large reservoirs can absorb large inflows by increasing the amount of water stored. Peak flows below some major reservoirs are reduced to essentially nothing as the dams perform their flood control functions. In a simplistic sense, all dams have a threshold for flood control. They can eliminate floods immediately downstream up to the point at which their storage capacity is exceeded. After they are filled, they exert no further control on stream flow. Of course, few reservoirs are operated in a static mode except small recreational impoundments such as Hume Lake. Most large reservoirs in the Sierra Nevada are multipurpose facilities whose releases are carefully controlled depending on inflows that are forecast, consequences of releases downstream, irrigation and power demands, and probability of additional precipitation.

Low Flows

Reservoir management also determines the releases under nonflood conditions. In the most severe cases, no water is allowed to flow in the natural channel; the entire natural flow is diverted elsewhere. Many streams in the Sierra Nevada, as in the classic example of inflows to Mono Lake, were completely dewatered below the points of diversion. In other cases, low flows are augmented, and the streams run at unnaturally high (and often constant) levels throughout the year. Below some hydroelectric powerhouses, discharges related to power demands can fluctuate wildly over a few hours. Afterbays allow regulation of the water released to the river.

Reservoir releases that partially resemble a natural hydrograph probably have the least adverse impact on downstream ecological processes. The minimum (and relatively constant) flow requirements on many water projects may serve to keep fish alive, but they are quite different from the flow regime that the aquatic community evolved with. Greater consideration of downstream ecological needs could be incorporated in the operations of many reservoirs without incurring major costs. The opportunities for alterations in release scheduling and their potential benefits and costs need to be explored on a project-by-project basis.

Changes in the flow regime also impact water quality. When stream flow is diminished substantially, there is less volume available to dilute contaminants entering downstream. In 1994, the U.S. Supreme Court decided that states had the authority under the Clean Water Act to regulate reservoir releases in the context of managing water quality. In some cases, reservoirs can improve riverine quality by allowing contaminants adsorbed on particles to settle out of the water column. However, this same process may be converting some reservoir beds into storage deposits of heavy metals (Slotten et al. 1994, 1995).

Water Temperature

Temperatures of streams below dams are affected by the volume and temperature of reservoir releases. If little water is released from a dam in summer, streams can become unnaturally hot because the radiant energy of sunlight on the channel is absorbed by a smaller volume of water than under natural flow conditions. Dams may be designed to release water from different depths in the lake. Reservoirs become thermally stratified like most natural lakes. In summer, stored water tends to be warmer near the surface, so releases from upper levels will result in higher temperatures than releases near the base.

Evaporation

The reservoirs behind the dams also export water to the atmosphere. Lakes lose water by evaporation roughly in proportion to their surface area. Creation of large expanses of open water by damming a river can significantly increase the opportunities for water losses from a watershed. Up to a meter of annual evaporation can be expected from reservoirs in most of the Sierra Nevada (Harding 1935; Longacre and Blaney 1962; Myrup et al. 1979).

Sediment Storage and Transport

Reservoirs dramatically change the sediment transport regime of a river. Virtually all bedload and most suspended load is deposited when a river enters the still water of a reservoir. The coarser fraction of the sediments forms a delta at the upper end. Deposits tend to be progressively finer toward the dam. When the water level is lowered, the streams cut through the deposits and relocate materials closer to the dam. Under some conditions, this channel incision can progress upstream (Galay 1983). With the extensive water development in most river basins of the Sierra Nevada, changes in sediment delivery should be considered throughout the basin. Each dam in the network affects the channel below it. With the presence of many dams upstream, contributing areas for sediment are often much smaller than contributing areas for water (in the absence of exports out of the basin).

Most of the geomorphic adjustments to dams occur downstream. These channel changes occur in response to shifts in sediment delivery and flow regimes, especially peak flows. Whatever water is released has significantly less sediment than when it entered the reservoir. Unless releases are minimal, the sediment-free discharge has the capacity to entrain and transport particles from the bed and banks of the downstream channel. Progressive lowering or degradation of the riverbed may occur after dam completion. Typical consequences of degradation include lowering of ground-water levels and consequent loss of riparian vegetation, reduction in overbank flooding and deposition of sediments and nutrients, bank erosion and loss of land, exposure of bridge foundations, and abandonment of diversion intakes (Galay 1983). The severity of channel incision depends on the size distribution of particles in the bed, characteristics of the channel, how the reservoir is operated and the sequence of flood events following construction (Williams and Wolman 1984). Downcutting seems to be greatest in rivers with fine-grained bed materials and where flood peaks are not greatly reduced by the dam. However, larger dams usually reduce flood peaks substantially and thereby limit the rate of degradation (Milhous 1982). Where channel incision occurs below dams, the finer particles are removed, and the larger cobbles and boulders are left behind. As the bed becomes coarser or "armored," it is more resistant to erosion and interferes with salmonid spawning. Also, downcutting decreases the channel gradient slightly, and degradation becomes somewhat self-limiting. The bed of the Yuba River below Englebright Dam has become armored with large cobbles and boulders but is still susceptible to incision during the largest floods (Kondolf and Matthews 1993). Conversely, flood control is so effective below both Pardee and Camanche Dams that channel degradation has not occurred and the gravels are immobile (BioSystems Analysis 1990, cited by Kondolf and Matthews 1993). Unfortunately, we lack any information about the condition of channels before placer mining and dam construction. Therefore, we are unable to make definitive statements about what constitutes natural channel conditions in most of the Sierra Nevada, although channels were unlikely to have been as armored as many are currently.

Where streambeds are not armored with large materials and are not actively degrading, fine sediments can interfere with fish spawning. Salmonids require gravels with sufficient pore space to allow interstitial flow to bring oxygen to eggs. Fine particles may be deposited between the gravels and limit the flow of water. Higher discharges are necessary on occasion to cleanse the gravels. Control of high flows by dams eliminates the opportunity to flush the fine sediments out of the spawning gravels. Many studies have been conducted in the past decade to define how much water is needed for this flushing function, and many rules-of-thumb have been suggested. However, variability in fluvial processes among streams illustrates the need to actually observe flows that begin to entrain particles of a particular size rather than depend on generalized procedures to estimate flow releases necessary to remove fine sediments from spawning gravels (Kondolf et al. 1987).

Limiting the size and frequency of floods below dams has also altered conditions for riparian vegetation. As total discharge and scouring flows decrease, riparian vegetation is able to become established in the former active channel (Williams and Wolman 1984). Roots stabilize the bank materials, and the plants slow overbank flows, which allows deposition of additional sediment. Gradually, the channel becomes narrower, and large trees occupy former parts of the channel. If allowed to become well established, mature riparian vegetation can resist significant flows. Confining the stream to a narrower channel can increase hydraulic forces on the bed and lead to incision and loss of riparian vegetation. To some degree, dams mimic the effects of long-term droughts on vegetation-channel interactions (Mount 1995). Depending on characteristics of the channel and plants, establishment of riparian vegetation can be enhanced by either higher or lower summer flows than occurred before dam construction. Encroachment of vegetation into river channels has been noted below Tulloch, Don Pedro, La Grange, and McClure Reservoirs (Pelzman 1973). Augmentation of flows at the receiving end of trans-basin diversion has widened channels and has pushed back riparian vegetation, as in the case of the upper Owens River.

Although larger dams seem to have sufficient space to store sediment for hundreds of years, at least at rates determined in the 1940s, smaller structures can become overwhelmed with sediment in just a few years. Unusually large floods can completely fill smaller diversion works, as occurred at Log Cabin Dam on Oregon Creek and Hour House Dam on the Middle Yuba in 1986 (Kondolf and Matthews 1993). Assuming that the dam is to remain in operation, the accumulated sediment must be removed. How that removal is accomplished can have an assortment of impacts. Dredging, trucking, and disposal of the sediments in a stable location has been a costly approach to the problem. Ralston Afterbay on the Middle Fork American River has had sediment removed on six occasions between its completion in 1966 and 1986 (Georgetown Ranger District 1992). The average annual rate of filling of about 80 m^3/km^2 (0.2 AF/mi^2) is not excessive compared with that of other basins, but the Ralston Afterbay has a capacity of only 3.4 million m^3 (2,782 AF) with 530 km^2 (205 mi^2) of unregulated contributing area above it (EA Engineering, Science, and Technology 1990). Location of suitable sites for long-term storage of removed sediments within a short distance from the reservoir has been difficult (Georgetown Ranger District 1992). The small forebays on Southern California Edison's Bishop Creek system have also required dredging of accumulated sediments. Estimates of the costs of dredging and transportation depend on access and distance to a disposal site and have ranged from \$26/m^3 (\$20/yd^3) (EA Engineering, Science, and Technology 1990) to about \$3,500/ m^3 (\$2,700/yd^3) (Kondolf and Matthews 1993).

Another option for removal of accumulated sediments is sluicing. Opening sluice gates or an outlet tunnel allows water levels to fall and sediment to be resuspended and flushed out with the water. This action creates a sudden pulse of sediment downstream. Problems have arisen when sluicing has been conducted during summer months, at times when flows are inadequate to disperse the redeposited sediment. Sluicing of Forbestown Reservoir on the South Fork Feather River in 1986 left a thin layer of sand over the entire channel well downstream of the dam. Another example was Democrat Dam on the Kern River in 1986. In the years following sluicing, high flows did not occur, and sand remained within the channel until scouring flows occurred in 1992 (Kondolf and Matthews 1993). Accidental releases of sediment occurred on the Middle Yuba River from Hour House Reservoir in 1986 and from Poe Dam on the North Fork of the Feather River in 1988. More than \$1 million was spent excavating sand out of the channel below Hour House Dam, but a flood during the early stages of the North Fork Feather cleanup conveniently flushed all the excess sediments out of the channel (Ramey and Beck 1990; Kondolf and Matthews 1993).

When sediment is flushed out of reservoirs at low flows, it will be redeposited close to the dam; however, when it is introduced at higher flows, it will usually be carried downstream and dispersed. Engineering approaches to letting sediments pass through dams during high flows are being considered at several sites. The Pacific Gas and Electric Company (1994) is designing pass-through systems to retrofit two of its dams on the North Fork Feather River. Sediment is rapidly filling the reservoirs, complicating operation of the dams, and accelerating turbine wear (Harrison 1992). Such pass-through systems could allow reservoir operations to interfere less with natural sediment transport and could have geomorphic benefits with regard to channel degradation below dams (Kondolf and Matthews 1993).

Failure

Catastrophic failure of impoundments is always a concern of those living below dams. Sudden releases of water also have great potential for dramatic environmental change. During the gold-mining era, dam failures were fairly common, both because of design flaws and because of intentional releases to rearrange gold-bearing sediments in the practice known as booming. Early debris dams were also intentionally destroyed to allow fresh access to impounded gravels and to create new storage space. Unintentional collapse of the English Dam on the Middle Fork of the Yuba (Ellis 1939; McPhee 1993) in June 1883 released almost 18 million m^3 (15,000 AF) of water suddenly and cleaned out much of the stored mining debris in that channel (James 1994). Excessive water releases from an upstream dam washed out a small dam on Bishop Creek in June 1909. Following failure of the Saint Francis Dam in the Ventura River Basin in 1929, the Division of Dam Safety of the Department of Water Resources has regulated larger dams and inspected them at least annually. Dams that are either more than 7.6 m (25 ft) tall and store more than 62,000 m^3 (50 AF) or, alternatively, more than 1.8 m (6 ft) tall regardless of capacity or impound more than 19,000 m^3 (15 AF) regardless of height are regulated by the Department of Water Resources (1988). Modern dams have little risk of failure; however, failures are not unknown. The best-known dam collapse in the Sierra Nevada in recent decades was that of the Hell Hole Dam on the Rubicon in December 1964 (Scott and Gravlee 1968). Failure of the North Lake Dam during a storm in September 1982 produced the largest flood of record on Bishop Creek and severely damaged one of the powerhouses. During the massive floods of February 1986, the coffer dam at the Auburn Dam site failed when diversion tunnels became clogged and the dam was overtopped. Structural failure of a penstock during high-pressure testing at the Helms Creek pumped storage facility in 1982 resulted in massive scouring of Lost Canyon (Chan and Wong 1989). Even partial failures, such as the gate damage on Folsom Dam in July 1995, can result in large releases of water and prolonged difficulties in project operation.

Eventually, some larger dams will become filled with sediment and no longer worth operating. The Federal Energy Regulatory Commission now has the authority to take dams out of service when they come up for relicensing. We have no real experience with what to do about a dam filled with sediment. Early debris dams on the Yuba and Bear Rivers just failed or were intentionally destroyed, and the sediments eventually moved downstream or became semistable terraces. However, that option probably won't be acceptable in the future. Plans are being made to decommission a dam on the Elwha River in Olympic National Park in Washington. Initial estimates suggest that removal of the dam could cost \$60–80 million and sediment removal could cost \$150–300 million. If estimates of reservoir sedimentation rates made during the 1940s turn out to be conservative, society will have a long time to think about what to do with the dams of the Sierra Nevada.

ROADS

Roads provide the most intensive modification of land surface properties relevant to the hydrology of common land-management practices. All vegetation is removed and prevented from reestablishment. Dirt-surfaced roads are compacted to a near-impervious state, and sealed and paved roads are completely impervious. Runoff from the surface is collected and discharged as potentially erosive flows at points below the road. Roads that are cut into slopes intercept subsurface water flow and bring it to the surface. Fill materials cover additional portions of the slope and often contribute to sediment yields slowly over time or catastrophically if they become saturated from subsurface water entry and then fail. Erosion from the actual roadbed of unpaved roads may be significant as well (Garland 1993; Adams 1993). Unauthorized use during wet surface conditions adds to the erosion of the road. A principal side effect of an extensive road network is the access that is provided to allow additional alterations. Few adverse impacts occur in the absence of roads. Avoidance of new road construction can minimize other potential impacts in currently unroaded areas.

Stream Crossings

The most serious impacts of roads occur where roads are in close proximity to streams or wetlands. Stream crossings by ford, culvert, or bridge have direct effects on the channel and local sediment regime. Although virtually any stream crossing will have some impact on the channel, careful engineering, construction, and maintenance can limit the severity. The basic problem just comes down to disturbing the bed, banks, floodplain, and terraces. Because the crossing is coincident with the channel, there is little opportunity to buffer the inadequacies of design or construction. Also, roadside ditches near the crossing drain directly into the stream, often contributing sediment to the stream. In past decades, very little attention was paid to stream crossings, and the cheapest alternative was usually chosen. Often, that choice was merely pushing a stack of cull logs into the channel and covering them with dirt. Installation of culverts sized only for summer flow, with anticipated reconstruction, was often a more cost-effective choice than a properly engineered crossing. Fortunately, engineering and construction practices have improved dramatically since crossings have become widely accepted as a potential problem (Furniss et al. 1991).

Forest Road Network

As with other disturbances, the proportion of a catchment that roads occupy greatly influences their net downstream impact. Sediment yield associated with roads has even been claimed to increase exponentially with their density in a watershed (California Division of Soil Conservation 1971a). Within national forests of the Sierra Nevada, gross road densities range from 0.6 km/km^2 (1.0 mi/mi^2) on the Inyo to 2.3 km/km^2 (3.6 mi/mi^2) on the Eldorado (U.S. Forest Service 1995a). There are approximately 28,000 km (18,000 mi) of roads on national forests of the Sierra Nevada. Construction of new forest roads has declined markedly in recent years, and reconstruction and obliteration have varied among years (table 30.6).

Sediment Production

A variety of studies have examined sediment production and mass movement occurrence from forest roads. As usual, there is little information from the Sierra Nevada. Studies of road impacts in northwestern California (e.g., Burns 1972; McCashion and Rice 1983), Oregon (e.g., Beschta 1978), Washington (e.g., Reid and Dunne 1984), Idaho (e.g., Megahan and Kidd 1972), and elsewhere have demonstrated increases in local erosion rates hundreds of times greater than natural rates as well as severalfold increases in sediment yield at the catchment scale. Sediment yield from roads is usually greatest in the first year following construction. Road construction and some timber harvesting in the 10 km^2 (4 mi^2) Castle Creek Basin near Donner Summit resulted in a fivefold increase in suspended sediment during the first year. Sediment yields decreased to twice the preconstruction levels during the second year (Rice and Wallis 1962; Anderson 1979). In a rapidly urbanizing part of the Lake Tahoe Basin, roadways were found to generate about half of the total sediment (California Division of Soil Conservation 1969). The presence of roads can increase the frequency of slope failures compared with the rate for undisturbed forest by up to hundreds of times (Sidle et al. 1985). Road location seems to be the most important single factor because it determines the opportunity of most other controlling influences to contribute to failure (Furniss et al. 1991; Rice and Lewis 1991). Road placement in topographic hollows caused ground-water flow to be impeded, leading to several major failures along a principal road in the Tahoe National Forest (McKean 1987). In the past, there was little rational planning or design for inslope versus outslope road surfaces and associated drainage works as a means of minimizing erosion.

Landslides and surface erosion can often be traced to haphazard road design, location, and construction (McCashion and Rice 1983). Forest roads constructed as part of a carefully planned system usually disturb much less ground, produce less sediment, and have lower construction and maintenance costs (Brown 1980). Road stability is often jeopardized by infrequent maintenance. A looming problem for the Forest Service is how to maintain some 28,000 km (18,000 mi) of roads in the Sierra Nevada with budgets inadequate even at present. Declining budgets have decreased maintenance activities overall and placed roads in lower maintenance categories than specified in the original design (Clifton 1992). If maintenance is not improved, quality of both transportation and streams will suffer. Lack of maintenance is often used as an excuse for failures resulting from poor design or construction (Seidelman et al. 1986). The road network must be acknowledged as both an investment and a liability for the long term.

TABLE 30.6

Kilometers of road activities in national forests in the Sierra Nevada by fiscal year (U.S. Forest Service, Region 5, Engineering Section).

Activity	1990	1991	1992	1993	1994
Construction	113	83	75	53	11
Reconstruction	620	326	323	453	307
Obliteration	NA	136	86	111	180

Rehabilitation

Casual examination of Watershed Improvement Needs Inventories on many of the national forests of the Sierra Nevada illustrated that fixing road problems is an overwhelming priority. The same engineering and construction skills needed to build roads can be used to repair, relocate, and obliterate roads that cause excessive water quality problems. Modern concepts of road location and design that are currently used to build new roads with minimal problems (Larse 1971) can be applied to reducing the adverse effects of existing roads (Clifton 1992). Reshaping road cuts, pulling back side-cast material, ripping compacted surfaces, and removing stream crossings were successfully employed in a watershed in northwestern Washington (Harr and Nichols 1993). The decommissioned roads survived with little damage two major storms that caused widespread failures of active roads. Sources of funding must be identified to maintain and stabilize the road network; otherwise, forests will be left with an analog to toxic waste dumps that get increasingly difficult to treat and cause additional impacts with the passage of time. Public education is also necessary to build acceptance for closing roads that damage public resources. Closure of unsurfaced roads during the wet season can also help to reduce erosion.

Streets and Highways

Although unsurfaced forest and rural roads have received most of the attention, urban streets and major highways can also create severe problems of slope instability and water quality (Scheidt 1967; Parizek 1971). Beyond sharing most of the impacts associated with forest roads, paved roads of higher standard have additional effects. Primarily, they are simply wider and affect more area per unit of length. A four-lane highway can occupy a substantial fraction of a small catchment. Their impervious surface can create overland flow over large areas where it was nonexistent before construction. They are designed for more traffic at higher speeds and so tend to be forced through the landscape, minimizing curvature and changes in grade instead of following the topography more closely. In partial compensation for the greater hill-slope alteration, highways are better engineered than lightly used roads. Large investments are made in adequate drainage structures, slope reinforcement, and revegetation. Nevertheless, mitigation for the sheer size and location of the highway projects is difficult at best. Major highways are immediately adjacent to portions of the Feather, North Yuba, South Yuba, Truckee, South Fork American, Merced, Walker, Kaweah, Tule, and Kern Rivers. Within cities and towns, the storm water drainage system for the entire road grid is often inadequate during large storms because communities tend to develop in a piecemeal fashion, rather than having a complete road and drainage network planned from the start. Contaminants from tire wear, fluid leaks, pet waste, and exhaust that accumulate on the roadway are washed off into the nearest waterway. Oils used for road dust abatement can also be problematic. For example, contamination of Ponderosa Reservoir on the South Fork Feather River with polychlorinated biphenyls (PCBs) was traced to the use of transformer oil on forest roads (Plumas National Forest 1988).

Deicing Agents

Chemicals used to remove snow and ice from roadways in winter can affect local water quality and roadside vegetation (Hawkins and Judd 1972; Scharf and Srago 1975; Goldman and Malyj 1990). During a heavy winter (1982/83), rock salt (sodium chloride) was applied to Interstate 80 near Donner Summit in an average quantity of about 45 metric tons per km (80 tons per mi) of roadway (Berg and Bergman 1984). Stream samples obtained about 0.5 km (0.3 mi) downstream from the last highway crossing of the channel contained up to 100 times more chloride and 10 times more sodium than water obtained just upstream from the highway (Berg and Bergman 1984).

FIRES, FIRE SUPPRESSION, AND POSTFIRE TREATMENTS

Catastrophic fire can produce some of the most intensive and extensive changes in watershed conditions of any disturbance. Within areas of intense fire, most vegetation is killed and stops transpiring, allowing soil moisture levels to remain high. Organic matter in the litter layer is volatilized and often forms a layer within the soil that reduces infiltration of water into the soil (see Poff 1996). Riparian zones that would not be harvested under current forest practices are often partially burned in intense fires. The combined effect of these changes is to increase total water yield and overland flow. As the proportion of overland flow increases, streams receive more water in less time than under prefire conditions, and peak flows may be increased. If a nearly continuous water-repellent (hydrophobic) layer is a few centimeters below the surface, the soil above that layer may become saturated and form shallow debris flows. With bare soil, increased overland flow, and lack of vegetation and litter, soil particles are more easily detached and transported. As with other impacts, the proportion of a catchment that is modified by fire and the location of the burned area with respect to the channel largely determine the effects on streams. A stream draining a watershed burned over 90% of its area will show much greater effects than a stream emanating from a similar watershed in which only the upper slopes and ridgetops were burned. Fire intensity is often highly variable over the landscape, and patches of unburned or lightly burned vegetation (especially near streams) can reduce the adverse effects of upslope areas that were intensely burned.

Water Yield

Fires affect water yield primarily by killing vegetation. Interception loss is decreased because of the loss of leaves, low vegetation, and litter. Transpiration is virtually eliminated wherever fire is intense. A daily cycle in stream flow reflecting transpiration demand during daylight hours in a catchment in Washington came to an abrupt halt following a catastrophic fire (Helvey 1980). Annual runoff in this completely burned watershed increased by 10–47 cm during the first seven years after the fire. Water yields in a small catchment in British Columbia that was burned over about 60% of its area increased by 25% on average for four years following the fire (Cheng 1980). Dramatic increases in flow of a small spring and a creek in the Sierra Nevada were observed following burning of riparian vegetation (Biswell 1989). A detailed modeling study for Pacific Northwest forests has suggested that a reduction in leaf area or basal area of about 50% is necessary before annual water-yield increases exceed about 50 mm (2 in) (Potts et al. 1989). Snow accumulation and melt rates might be expected to increase from opening a forest canopy by fire, and such effects have been observed in Washington and British Columbia (Helvey 1980; Cheng 1980) but not in Idaho (Megahan 1983).

Peak Flows

Peak flows can be expected to increase following significant fires because of higher soil moisture resulting from reduction of transpiration, decreased infiltration, and higher rates of snowmelt. Infiltration is usually the most important influence, and it is decreased in two ways. Removal of vegetation and the litter layer exposes bare mineral soil to raindrop impacts, which can physically force the soil particles closer together and disperse soil aggregates into surface pores, thereby reducing the infiltration capacity. Fires also vaporize organic compounds in the litter layer, some of which move into the soil until the vapor condenses and forms a layer that is water repellent, or hydrophobic (De Bano 1981). These layers tend to be more coherent in coarse-textured soils (e.g., decomposed granitics), under very hot fires, and where a thick litter layer and/or organic horizon was present (De Bano 1981; Poff 1989b). The continuity of such layers, which may be a function of fire intensity and litter distribution, determines their overall impact on hill-slope water movement. Additionally, larger macropores from roots and animals allow some water movement through the hydrophobic layers (Booker et al. 1993). Although the water-repellent layers tend to break down within a year or two, those formed in soils that are somewhat hydrophobic even without burning may be more persistent (Poff 1989b). Under some conditions, a hydrophobic layer forms on the surface of the soil and acts as a binder and sealant, maximizing overland flow while minimizing erosion (see Poff 1996). As usual, there is a lack of measured hydrologic response to fire in the Sierra Nevada. A variety of studies elsewhere in the western United States have demonstrated dramatic increases in peak flows following wildfire (Tiedemann et al. 1979).

Sediment Yield

In general, sediment yields increase markedly after fires, particularly if riparian vegetation was burned. Most of the sediment response seems to be from the channels themselves. In the absence of streamside vegetation, soil particles move into the channels from dry ravel erosion, and the banks become less stable. Increases in total discharge and peak flows result in channel erosion. Debris torrents may scour streams if extreme climatic events follow the fire (Helvey 1980; Kuehn 1987). If the fire is particularly hot, woody debris that helped stabilize the channel may be destroyed. Erosion from the general land surface usually increases, but it may not always be as important a delivery mechanism as has been assumed (Booker et al. 1993). Erosion from plots in brushland near North Fork in the San Joaquin River Basin increased by 200 to 400 times after repeated burning (Lowdermilk and Rowe 1934). In Dog Valley in the eastern Sierra Nevada near Reno, a single storm produced about 600 m^3/km^2 (1.3 AF/mi^2) of sediment from a burned catchment while an adjacent unburned area yielded only a trace of sediment (Copeland 1965). Under extraordinary rainfall, gully erosion, sheet erosion, and a debris torrent removed more than 19,000 m^3 (15 AF) of material from a burned catchment of about 0.8 km^2 (0.3 mi^2) in the headwaters of the South Fork of the American River in 1982 (Kuehn 1987).

Nutrient Yield

Fires provide an opportunity for nutrients that have been stored in vegetation and soils to move into streams. Materials that are not volatilized and lost to the atmosphere are left in ash on and near the soil surface in forms that are readily mobile. A variety of studies throughout the West have demonstrated that concentrations of nitrates and other ions in streams usually increase dramatically after fires (Tiedemann et al. 1979). However, the background concentrations of these constituents in streams draining healthy forests are typically so low that the relative increases following fires appear to be huge even though the absolute amounts often remain almost negligible or at least below water quality standards. Nevertheless, there is potential for a nutrient flush to dramatically increase algae in streams, which can have additional consequences. There is also the potential for large nutrient losses associated with physical erosion of soil particles that often carry nutrients with them (Tiedemann et al. 1979). A study of the chemistry of Sagehen Creek north of Truckee following the Donner Burn in 1960 did not detect any change in the ionic composition of the stream relating to the fire, which did not burn the riparian zone (Johnson and Needham 1966). The inevitable fires in urban intermix zones have the potential to release a variety of chemicals and combustion products into the aquatic environment. Reconstruction can keep soils bare and disturbed for years.

Aquatic Effects

Studies of the aquatic effects of a fire on the Plumas National Forest demonstrate how both physical and biological features of the stream change over time (Roby 1989; Roby and Azuma 1995). The lower two-thirds of this catchment, including riparian vegetation, was thoroughly burned. Initially, the channel widened in response to presumed higher flows of water and sediment. However, as vegetation became established and the watershed recovered, the cross sections of the channel returned to their prefire areas within six years of the burn. Partial recovery of the invertebrate community seemed to have occurred relatively quickly. No differences in community similarity were noted between burned and unburned reaches one year after the fire, and density and taxa richness were comparable within three years. However, significant (though declining) differences in a species-diversity index between the burned and unburned reaches remained throughout eleven years of monitoring (Roby and Azuma 1995).

Fire Suppression

Fire suppression during this century has created forests with greater density of vegetation than in the past (Chang 1996; Skinner and Chang 1996; Weatherspoon 1996). This forest structure has current and potential hydrologic consequences.

The present situation may decrease yields of water and sediment somewhat compared to a natural fire regime (if impacts of other activities, such as residential development and road construction, are ignored). Although these changes cannot be quantified, transpiration from the dense forests should be at or near maximum, and a more open forest structure resulting from more frequent fire could be assumed to use less water. The dense vegetation also increases the opportunity for intense conflagrations (Chang 1996; McKelvey et al. 1996; Skinner and Chang 1996) that could produce major increases in water and sediment yields. There is a basic contrast between moderately higher stream flow and sedimentation on a semiconstant basis with relatively frequent low-intensity fires and the other extreme of lower stream flow with less sediment for now with the looming possibility of damaging floods and sediment loads from less-than-perfect fire suppression.

Actual on-the-ground fire-fighting activities, as opposed to the general policy of fire suppression mentioned above, also have impacts on water resources (California Division of Forestry 1972). In general, the net effect of such actions is probably less than doing nothing, given current fuel loads. The principal impacts of the past, which presumably are rare under current practices, involved operation of heavy equipment in streams and riparian zones and down the fall line of slopes. In some large fires, an extensive network of fire breaks may be bulldozed and require rehabilitation. Aerial application of retardants can also have adverse aquatic impacts (Norris and Webb 1989).

Postburn Activities

Following fires, there is usually a strong desire by landowners, agencies, and the public to react quickly. Hastily constructed fire lines often require obliteration or drainage; otherwise, allowing natural recovery processes to function may often be the best policy (Beschta et al. 1995). For example, natural regrowth on north-facing slopes virtually stopped erosion within three years of a fire in Idaho that initially produced more than 1,000 m^3/km^2 (2.3 AF/mi^2) of sediment (Megahan and Molitor 1975). Unfortunately, the state of the art in postfire rehabilitation remains poorly developed. Despite vigorous implementation of various actions over vast areas of the western United States, there has been minimal monitoring of the effectiveness of those actions. We therefore have very little collective experience or documentation of what works and what doesn't work. There are a lot of different treatments recommended in rehabilitation handbooks, but there is little apparent basis for the recommendations measured as success or failure in years following the prescription. There is active debate among fire specialists, soil scientists, hydrologists, and ecologists about some very basic issues. For example, rye grass seeding has been encouraged for years as a means of getting some vegetation cover in place as quickly as possible. Despite evidence compiled over thirty years that it inhibits establishment of native vegetation, results in less total cover after a couple of years than in nonseeded areas, and may even enhance net soil loss or have other adverse effects (Krammes and Hill 1963; Booker et al. 1993; Roby and Azuma 1995), many people seem to view it as a panacea. Contour felling of logs and straw-bale check dams to trap sediment are other widely accepted practices that may be less effective than generally assumed. These techniques appear to meet certain objectives in some situations (e.g., De Graff 1982), but their indiscriminate use is ineffective at best and may be counterproductive. One of the lessons of the catastrophic fire in Oakland in 1991 was that we simply didn't know what erosion control measures would be appropriate.

In the past decade, salvage logging of dead and dying trees has become quite controversial, with some people feeling it is just an excuse to cut trees while others feel it is the only thing maintaining their business. Postfire salvage operations influence aquatic recovery in a variety of ways. Perhaps most important in the present economic climate, salvage sales have potential to generate revenue for watershed rehabilitation, which unfortunately seems to be underutilized. Culverts are often replaced with larger structures in anticipation of larger flows; the soil disturbance from reconstruction is much less than what would occur if the road were to fail. The replacements are probably better designed than the original and should be more stable in the long term. Some roads may be decommissioned. Logging slash can be used to provide some physical protection for soils. Cutting shallow-rooted trees avoids the displacement of their root masses if they were to be blown over. On the negative side, logging operations disturb soils when the soil is particularly sensitive to compaction and erosion in the absence of cover and organic matter. Significant ground disturbance during a salvage sale of the Clark Burn in the Last Chance Creek watershed of Plumas County led to severe erosion during a thunderstorm (Cawley 1991). Where strong hydrophobic layers have developed, such disturbance might be valuable in promoting infiltration (Poff 1989b). However, on slopes subject to deeper mass failure, hydrophobic layers may be desirable as a means of limiting accumulation of water in the soil. If postfire treatments of salvage logging and site preparation prevent rapid reestablishment of low vegetation, resulting erosion can be greater than that directly produced by the fire. Timing of major storms relative to the amount of bare soil is a dominant influence. A fire in the Tuolumne River Basin in 1973 was not immediately followed by any major erosion-producing events (Frazier 1984). However, widespread ground disturbance associated with salvage operations prolonged susceptibility of soils to erosion. Eventually, substantial rain-on-snow events provided the energy for serious rill, gully, and bank erosion, which resulted in significant soil losses (Frazier 1984).

The principal objectives of postfire rehabilitation work should be to avoid making things worse; repair potential problems from fire-fighting activities (e.g., bulldozed fire breaks); enhance establishment of native vegetation to provide soil cover, organic matter, stream-bank stability, and shade as quickly as possible; attempt to stabilize channels by nonstructural means; minimize removal of large woody debris from streams; minimize adverse effects from the existing road network; schedule operations to minimize exposure of bare soil; and allow natural processes to heal the landscape.

Fuels Reduction

A major program of fuels reduction could increase gross water yields, peak flows, and sediment yields, depending on how extensively particular treatments are applied. As part of the investment in such a program, a team of soil scientists, hydrologists, and aquatic ecologists must actively participate to minimize the adverse effects on soil productivity and the aquatic environment. Although we have created forests that carry a high risk of damage to aquatic resources, pursuit of quick fixes in an atmosphere of crisis carries substantial risks as well (Beschta et al. 1995).

TIMBER HARVESTING

Harvesting of trees, especially in large clear-cut blocks, is commonly perceived as a major impact on the hydrology of river basins. Although timber removal has dramatic effects on the water balance of the immediate site, consequences at the catchment scale are not so obvious. As with many of the land management activities discussed in this chapter, the proportion of the catchment that is treated and the proximity of the treatment to water courses are critical in determining the impacts on water quantity, timing, and quality. In addition, associated activities such as road construction, yarding, slash treatment, and site preparation usually have much greater impacts than just the cutting of the trees. Hydrologic effects of selection harvests are generally considered to be less problematic than those of clear-cutting because the remaining trees remove soil moisture and provide some protection to the soil surface (Anderson et al. 1976). Harvest effects must also be considered with respect to time. Fortunately, trees and other plants quickly reoccupy most harvested areas, reestablishing protection from raindrop impact, uptake of soil moisture, deposition of organic matter to the soil, and support of soil masses by roots. Slopes are most vulnerable to surface erosion and generation of excess water immediately after harvest or site preparation, but they have minimal root strength about a decade after harvest (Ziemer 1981).

Water Yield

Harvesting timber has the potential to increase annual water yields via several mechanisms. Removal of all trees removes the possibility of any interception losses over the former area of the canopy. However, evaporative loss from rain and snow detained in tree canopies may be a relatively small component of the water balance of forests in the Sierra Nevada and has been estimated at about 30 mm (1.2 in) per year (Kattelmann et al. 1983). Removing trees also terminates transpiration in rough proportion to the extent of removal and the ability of remaining plants to use the water. The depth and moisture storage capacity of forest soils largely control the amount of reduction in evapotranspiration from harvesting (Zinke 1987). When trees are harvested at the base of a slope near a stream, a large fraction of the soil water formerly used by those trees will enter the stream. If trees are cut near the top of a slope, residual trees below the area harvested may use much of the "excess" water not transpired in the harvest unit, and relatively little of this water may reach the stream. More than one hundred studies of stream-flow response to forest harvesting have been conducted around the world. These studies have been reviewed by many authors (e.g., Anderson et al. 1976; Bosch and Hewlett 1982; Ponce 1983; Kattelmann 1987; Reid 1993; Marvin 1995, 1996). In almost all cases, stream flow increases as basal area (and evapotranspiration) declines. As vegetation regrows on the site, evapotranspiration increases and stream flow declines correspondingly (e.g., Troendle and King 1985). Intensive timber harvesting under the usual constraints of national forest management could increase stream flow in most Sierra Nevada rivers by 1%–1.5% (6–9 mm [0.24–0.35 in]) (Kattelmann et al. 1983; Rector and MacDonald 1987).

Peak Flows

Although most work to date has been done on changes in the seasonal water balance, short-term changes with respect to storm response and flood augmentation are also important. Timber harvesting can affect peak flows through two principal mechanisms: maintenance of high soil moisture in the absence of evapotranspiration and higher rates of snowmelt during rain events. In a simplistic sense, less rainfall is required before runoff is produced if trees are not using stored soil moisture than if trees occupy the site. Creation of openings in the forest alters energy exchange and snow storage. During warm storms, most snowmelt occurs through turbulent exchange processes (condensation and convection), which are more effective at higher wind speeds. The greater wind speeds in forest clearings compared with dense forests increase the rate of snowmelt in the clearings relative to that under tree cover (Harr 1981; Berris and Harr 1987). Considerably more snow is found in forest openings than under forest canopies because wind deposition of snow is favored in openings and much of the canopy-intercepted snow drips off as liquid water and enters the soil. In the intermittent snowpack zone, this difference in deposition can result in an absence of snow under trees while several centimeters of snow water equivalence is available in openings to add water to storm runoff.

Potential effects of land management on flood generation are most pronounced during small and moderate storm events and in small catchments (Hewlett 1982). During rare, intense storms, the differences in soil moisture storage or snow available for melt are almost incidental compared to tens of centimeters of rainfall (Ziemer 1981). At the river basin scale, flood peaks in the main river depend on synchronization of flood peaks from tributaries, which could be affected by drastic changes in land cover either positively or negatively.

Sediment Yield

Mass movements can be enhanced by timber harvesting by maintaining higher levels of soil moisture in the absence of evapotranspiration and loss of the reinforcement of the soil mass provided by roots (Sidle et al. 1985). On the average, the structural integrity of hill slopes is at a minimum about nine years after harvest, when the decay of old roots is not yet compensated for by the growth of new roots (Ziemer 1981). Roads tend to cause far more problems with respect to mass movement than does timber harvesting, and documentation of logging as a direct cause of mass failure in the Sierra Nevada has not been found.

Brushland Management

Conversion of brush fields to grass could increase stream flow and probably sediment yields at lower elevations (Anderson and Gleason 1960; Turner 1991). A proposal to manage about 130 km^2 (50 mi^2) of chaparral in the lower Feather River Basin with prescribed burning and some conversion to grass estimated that annual stream flow would increase by more than 3 million m^3 (2,500 AF) (California Department of Water Resources 1983b). Risks of increased erosion from such a program (e.g., Pitt et al. 1978) would need to be balanced against those from catastrophic fire. Conversion of brush fields to coniferous forest at higher elevations could delay snowmelt (Anderson 1963).

Observed Impacts

From a mechanistic point of view, forest harvesting in the past couple of decades has had limited opportunity to cause major changes in stream-flow volume, peak discharges, or sediment yield. In most river basins, the fraction of the basin area harvested per decade does not seem sufficient to cause major hydrologic responses. Nevertheless, peak flows in the South Fork Tule River appear to have increased in recent decades coincident with extensive road building and logging (see Marvin 1996). The level of harvesting since World War II has probably increased water yield somewhat in smaller catchments, but any increase may have been partially compensated for by increases in total vegetation density resulting from effective fire suppression over the same period. Unfortunately, neither influence can be quantified with any confidence. Similarly, we lack the appropriate data to observe whether modest changes have actually occurred. Except in the Tule River case (see Marvin 1996), no changes in the stream-flow record that clearly exceed natural variability have been noticed. With respect to sediment yield, data are not currently available to show any change over the past few decades at larger scales except in the Mokelumne River, where sediment yield has increased dramatically (EBMUD 1995). Appropriate baseline data in reservoir surveys could be used to determine if sediment yields have increased as a cumulative result of all types of land disturbance. Carefully performed follow-up surveys are needed to find out if land-management activities have made a significant difference.

At the smaller watershed scale, there is at least some observational evidence to suggest that land management affects the hydrology of small streams in the Sierra Nevada. Again, the impacts are the result of all activities associated with harvesting, such as road construction, skidding, and site preparation. Landslides that begin at roads and that are the only occurrences of mass movement in a catchment can be attributed to management activities. Similarly, when the only pools in a channel reach that are filled with silt are those immediately below clear-cuts that included the riparian zone, we can infer some cause and effect. However, even when impacts are overwhelming at the local scale, they are quickly masked downstream because few other contributing catchments were treated in the same way. A few studies in the Sierra Nevada have indicated impacts at the small watershed scale. Suspended sediment increased in the 10 km^2 (4 mi^2) Castle Creek Basin near Donner Summit during the first year following road construction and timber harvesting (Rice and Wallis 1962). Sediment captured in weir ponds below a catchment 1.2 km^2 (0.5 mi^2) in area on the Sequoia National Forest increased severalfold after road construction and harvesting (McCammon 1977). Stream reaches in twenty-four small streams in the Sierra Nevada and Klamath Mountains had significantly higher indices of stored sediment than corresponding control reaches (Mahoney and Erman 1984). Water yields from Berry Creek (20 km^2 [7.5 mi^2]) near Yuba Pass seemed to have increased substantially following harvests on less than half the basin (Kattelmann 1982). Peak flows may have increased in part of the Mokelumne River Basin as a result of extensive harvesting (Euphrat 1992). Unfortunately, long-term paired-catchment studies have never been performed in the Sierra Nevada, so we are left attempting to infer impacts from experiments elsewhere.

Aquatic Effects

Studies that began in the 1970s on several streams in the northern Sierra Nevada and Klamath Mountains demonstrated that communities of aquatic invertebrates changed significantly in response to upstream logging (Erman et al. 1977; Newbold et al. 1980; Erman and Mahoney 1983; O'Connor 1986; Fong 1991). Some of the aquatic effects have persisted for two decades (Fong 1991). The aquatic communities are particularly sensitive to logging-related disturbance within 30 m of the channel (Erman and Mahoney 1983) and perhaps within 100 m (McGurk and Fong 1995). In a recent study of forest management effects on aquatic habitat in the Sierra Nevada, data were collected on channel characteristics, aquatic habitat, fish abundance and health, aquatic invertebrate abundance, large woody debris, water chemistry, and management history in twenty-eight different basins in the Sierra Nevada (Hawkins et al. 1994). In general, natural variability in the measured attributes masked effects of management activity. Response of aquatic organisms to disturbance in the watersheds tended to be small compared with response to natural factors. Observed increases in nutrient loading and temperature appeared to enhance abundance of some taxa without any noticeable adverse impacts on others. Most of the communities in the observed streams appeared to be limited by food resources. The study noted, "We cannot at this time either measure or predict with any degree of reliability or confidence the cumulative effects most types of land use practices will have on natural ecosystems" (Hawkins et al. 1994, 1).

GRAZING

Grazing of domestic livestock has probably affected more area in the Sierra Nevada than any other management practice (Menke et al. 1996). Over the past century and a half, cattle and sheep have been virtually everywhere in the mountain range that provides forage. The near-ubiquitous presence of grazing animals has left few reference sites that we can be certain were never used by livestock. The best approximations to ungrazed conditions are those areas that have been rested for a few decades. Even Sequoia National Park was grazed until 1930 (Dilsaver and Tweed 1990). The absence of reference sites leaves us uncertain about what an ungrazed stream looks like and how it functions. This uncertainty is not merely an academic concern. Major questions of grazing management depend on our confidence in our understanding of how natural systems function without human-induced perturbations. For example, we can hypothesize that overgrazing on the Kern Plateau in the 1800s contributed to the widespread arroyo development and conversion of wet meadows to dry terraces. There are several lines of evidence that support that hypothesis. However, we would have more confidence if one of the early shepherds had invested a couple of summers in fencing off an entire watershed and preventing entry just to satisfy the curiosity of future generations. This problem of uncertainty exists to some degree with all impacts, but there are many areas that were not mined, dammed, logged, roaded, or urbanized. There just are not many that were not grazed.

In 1924, Aldo Leopold wrote, "Grazing is the prime factor in destroying watershed values," in reference to an overgrazed site in Arizona. Since then, debate has continued about the validity of similar statements applied to watersheds throughout the West. The impacts of grazing that relate to hydrology depend primarily on the behavior of the animals: feeding, drinking, producing waste, and traveling. If the animals remain in one place too long and consume much more than about half the available forage, vegetative recovery may be impaired and an excessive amount of bare soil may be exposed to erosive rainfall (Fleischner 1994; Committee on Rangeland Classification 1994). Although the amount of consumption that constitutes "overgrazing" depends on vegetation and site characteristics (Menke et al. 1996), half of the initial forage is a useful, though admittedly crude, rule of thumb (California Division of Forestry 1972). When insufficient vegetation remains after grazing, raindrop impact can change surface conditions and consequently reduce infiltration and increase erosion (Ellison 1945). Soil can become compacted by the repeated pressure of moving animals, especially if the soil is wet. The combination of soil exposure and compaction can decrease infiltration and increase surface runoff. If infiltration capacity is severely limited on a large fraction of a catchment, the extra runoff can quickly enter streams and generate higher peak flows (e.g., Davis 1977).

Surface and Channel Erosion

Exposure of mineral soil and enhanced overland flow also accelerate erosion. A variety of studies around the West have found dramatic increases in sheet erosion and gullying in overgrazed sites compared with ungrazed areas (Fleischner 1994). Severe gully erosion in the uplands of the North Fork Feather River has been caused by decades of overgrazing (Soil Conservation Service 1989). Nevertheless, the worst erosion problems associated with grazing typically occur near streams. Cattle tend to congregate in riparian areas for obvious reasons: abundant food, water, shade, and lower temperatures. Consequently, riparian vegetation is overgrazed, banks are trampled and eroded back, and bed deposits are disturbed. All this activity adds significant amounts of sediment directly to the stream. Dislocation of sediments in the streambed by moving animals augments suspended sediment. Degradation of riparian vegetation permits bank erosion to accelerate under the more frequent peak flows that are caused by the decrease in infiltration capacity. About half of the channels in the Meiss allotment in the Upper Truckee River watershed were identified as being in fair or poor condition as a result of overgrazing (Lake Tahoe Basin Management Unit 1993). Changes in channel morphology have been related to overgrazing in headwater streams tributary to the Carson River (Overton et al. 1994). Elimination of riparian vegetation by overgrazing in the broad alluvial valleys of the North Fork Feather River has led to rapid channel widening and massive sediment loads (Hughes 1934; Soil Conservation Service 1989). In other areas, such as meadows of the Kern Plateau and San Joaquin River Basin, downcutting has followed overgrazing (e.g., Hagberg 1995). Development of these deep arroyos has lowered the local ground-water table and transformed wet meadows into dry terraces supporting sagebrush. The possibly compensatory effects of less bank storage and less transpiration by vegetation determine whether low flows in summer are decreased or increased by the downcutting. A recent study of channel characteristics between pairs of currently grazed areas on national forests and long-rested areas in national parks in the Sierra Nevada found significant differences in bank angle, unstable banks, bed particle size, and pool frequency (U.S. Forest Service 1995b). Significant differences in undercut and unstable banks were also observed between grazed areas and adjacent fenced exclosures with a few years of rest.

Water Temperature

Removal of riparian vegetation and channel widening by grazing expose the stream to much more sunlight. Therefore, stream temperatures in summer may be several degrees higher than if shade remained. In winter, the absence of riparian vegetation may allow wind scour of snow in exposed creeks in high-elevation meadows. With less snow serving as insulation, ice formation may be greater than in creeks with vegetation capable of trapping more snow, which provides insulation itself. These artificial changes in temperature impact aquatic organisms that rely on a more natural temperature regime.

Water Pollution

Congregation of cattle in and around streams provides a direct pathway for nutrients and pathogens to degrade water quality (Springer and Gifford 1980; Kunkle 1970). High nutrient loads promote the growth of aquatic algae, which can virtually clog streams at low flow. An example of proliferation of aquatic plants apparently augmented by cattle is found in the Owens River above the Benton Crossing road. High levels of coliform and other bacteria have been found in streams heavily used by livestock (Lake Tahoe Basin Management Unit 1993; Central Valley Regional Water Quality Control Board 1995). Cattle grazing in backcountry areas provides a source of Giardia cysts (Suk et al. 1985).

Associated Impacts

There are a variety of ancillary effects of grazing. Road construction to provide access to range improvements has similar impacts to those of roads in general, depending on the location and design. Springs are extensively developed for stock watering, at the expense of native biota. Irrigated pasture consumes immense quantities of water for a low-value product (Romm et al. 1988).

Improved Practices

Improved grazing practices as applied to the Sierra Nevada have the potential for limiting many of the possible adverse impacts (Albin-Smith and Raguse 1984). Major changes in grazing practices in some parts of the eastern Sierra Nevada have recently occurred. A study is currently under way monitoring the response of macroinvertebrates and fish to riparian fencing and rest-rotation management (Herbst and Knapp 1995a, 1995b). Degraded channels in the Meiss allotment at the south end of the Lake Tahoe Basin led to a decision by the Forest Service to rest the allotment for five to fifteen years until stream-bank vegetation has recovered (Lake Tahoe Basin Management Unit 1993). However, this decision was overturned on appeal by the regional forester in 1995.

URBAN, SUBURBAN, AND EXURBAN DEVELOPMENT

The population of the Sierra Nevada foothills is expected to increase rapidly in the next few decades (see Duane 1996a). Conversion of forests and woodlands to residential and commercial land uses has several serious hydrologic effects on local streams (Lull and Sopper 1969). Such conversions dramatically alter the disposition of rainfall or snowmelt on the landscape by reducing infiltration capacity of the surface to zero or near zero. Land that was formerly well vegetated and rarely, if ever, produced overland flow is converted to an impervious zone where virtually all precipitation becomes immediate runoff. The extent of such changes and the ability of adjacent land to absorb the additional runoff determines the response of streams. Gutters, ditches, drains, channels, culverts, and storm sewers are intended and designed to convey runoff as rapidly as possible to streams. The combination of greater volume of runoff, faster generation of runoff, and greater channel efficiency moves more water downstream faster than under natural conditions. This convergence of large volumes of water in short periods of time produces frequent floods downstream from even modest rainfall (Leopold 1968). The more frequent floods lead to channel enlargement by erosional processes (Dunne and Leopold 1978; Booth 1990). Unfortunately, stream gauging stations have not been placed in strategic locations to actually record changes in stream-flow regimes in response to development in the Sierra Nevada.

Impervious Surfaces

The proportion of impervious area created by residential construction is a rapidly decreasing function of lot size. Small urban lots can be effectively sealed over three-quarters of their surface area, while lots of 0.4 ha (1 acre) might be impervious on only 10%–15% of the area. So-called low-density residential lots can be 20%–30% impervious surface (California Division of Soil Conservation 1971b). Larger parcels would have much smaller proportions rendered impermeable by construction. Although impervious area is a small fraction of dispersed "ranchette" development, the amount and intensity of conversion of natural vegetation to other uses, such as orchards, vineyards, pasture, ostrich ranches, and Christmas tree farms, will determine the hydrologic impacts. The area occupied by roads is closely associated with the density of structures. In addition, the quality of road location and construction will influence the potential for adverse effects. Poorly designed roads for subdivisions are a principal source of sediment in Nevada County (Gerstung 1970).

Channelization

Channelization (forcing streams into engineered waterways) has been practiced in the Sierra Nevada since the first miners' ditches for water supply were constructed and rivers were confined in wooden flumes while their gravels were excavated. During the mining era and subsequent development of water resources for hydropower, municipal, and agricultural uses, streams were put into artificial channels to get the water to another place where it was wanted. Around roads and towns, the usual objective of channelization is to get water away from a place where it is not wanted. Creeks of all types and sizes have been relocated, smoothed, and straightened to get water away from roads and homes as quickly as possible. These ditches, canals, and storm sewers enhance the flood-producing effects of general land conversion by routing the extra runoff away from the town or road much more quickly than under natural conditions. Peak flows are augmented downstream, but that is typically beyond the concern of the local channelization project. Flooding in Roseville during January 1995 was a classic example of this phenomenon. Failure of artificial drainageways and streets to perform as expected can also cause damage within the community attempting to control the runoff, as occurred in Cameron Park in 1982 and 1983 (Soil Conservation Service 1985). At higher elevations, runoff rates from snowmelt may also be accelerated where infiltration is limited in significant fractions of a watershed (Buttle and Xu 1988).

Vegetation Removal

Other hydrologic impacts of conversion to residential and commercial land uses include reduction of interception and transpiration functions of trees and other vegetation via their removal. All plants intercept and store some proportion of the precipitation received. Water retained in the canopy eventually evaporates. Continuous vegetation cover can reduce the amount of water reaching the ground substantially, depending on storm amounts and frequency. Removing the vegetation largely eliminates this function. Whatever replaces the plants usually has some interception capacity. However, roofs, latticework, and other structures do not transpire. So, vegetation conversion eliminates the active removal of soil moisture and its transfer to the atmosphere. Soil moisture would remain higher in the absence of transpiration if soil moisture recharge could take place through whatever covers the soil instead of vegetation. Where impervious areas are constructed, recharge of shallow and deep ground water is minimized. If the total area of limited infiltration is a significant fraction of a catchment, ground-water levels will decline. Stream flow during nonstorm periods that was formerly generated by seepage from ground water will also decline. Ground-water pumping for domestic and irrigation supply can exacerbate the problems of restricted recharge. In some cases, irrigation return flows may augment summer stream flow.

Water Pollution

The changes in runoff are closely related to declines in water quality associated with urban development. Enhanced runoff washes various contaminants off roofs, streets, parking lots, gutters, horse corrals, and golf courses and into streams. Diminished base flow increases the concentration of residual pollution entering after the floods. Urban pollutants include soil particles, nutrients, heavy metals, toxic organic chemicals such as pesticides, oil and grease, fertilizers, oxygen-demanding materials such as yard waste, and bacteria and other pathogens (Terrene Institute 1994). The diversity of sources makes control difficult, but best management practices are being developed and applied to control urban runoff. Development of riparian areas limits opportunities for filtering, uptake, and assimilation of contaminants. The combined effects of changes in runoff regime, water quality, and channel structure resulting from urbanization have profound effects on aquatic life. Eliminating infiltration on as little as a tenth of the catchment area led to declines in population of fish and amphibians near Seattle (Booth and Reinelt 1993).

Accelerated Erosion

Removal of vegetation, grading, and exposure of bare ground allows erosion to increase dramatically, especially during construction. Freshly cleared land for a new subdivision in Plumas County produced enough sediment in a single intense storm to kill 80% of the aquatic life in Big Grizzly Creek (California Division of Soil Conservation 1971b). In Nevada County, more than a third of the total length of streams has been damaged by siltation and stream-bank erosion resulting from subdivision development (Gerstung 1970). Erosion rates in the Middle Creek watershed near Shasta City increased more than twentyfold following urban development (Soil Conservation Service 1993). Residential construction around Lake Tahoe has been a major contributing factor in accelerating erosion and increasing nutrient inputs to the lake (Tahoe Regional Planning Agency 1988).

Sewage

Effluents from wastewater treatment facilities and leachates from dispersed septic systems add nutrients to ground water and streams. Breakdowns and spills from sewage facilities can introduce pathogens to receiving waters. Leaks from sewer lines have been recognized as an important source of nutrients in the Lake Tahoe Basin (Tahoe Regional Planning Agency 1988). Wastes from domestic animals and pets can also contaminate streams. Organic wastes can deplete dissolved oxygen in streams as well. Water quality was considered impaired in streams receiving wastewater from Nevada City, Grass Valley, Placerville, Jackson, and the Columbia-Sonora area (Central Valley Regional Water Quality Control Board 1991). Small sewage treatment plants serving recreational developments often suffer from inadequate financing, technology, and management (Duane 1996a). A facility at California Hot Springs alternately released excessive amounts of barely treated sewage or chlorine for several years. Giant Forest Village in Sequoia National Park was largely closed during the winter of 1994/95 because of poor performance of the wastewater treatment facility. Disposal of solid waste also has the potential to contaminate ground water and streams. Older landfills were probably not carefully located or designed and may be producing hazardous leachates. Location of new landfill sites is so difficult that Tuolumne County is planning to export its garbage to Lockwood, Nevada.

Water Supply

Supplying water for new development is problematic in many parts of the Sierra Nevada, which is ironic given the high runoff production of the mountain range. Coping with the seasonal distribution of runoff usually involves construction of storage reservoirs when large numbers of users are involved. Beyond the seasonal availability, most of the difficulties are legal and financial rather than physical. Surface waters are already overappropriated in many watersheds. Newcomers may find that all the local water is already claimed. Also, there seems to be a widespread belief that water should be supplied free or for a minimal charge—that somebody else (i.e., "the Government") should subsidize water supplies. Communities are often in favor of augmenting their water supplies for new development until they find that they are expected to share the cost. The Calaveras County Water District has financed its water development through the sale of hydroelectricity. Tuolumne County is faced with large costs and potentially high water rates from its redevelopment of the Lyons Reservoir system, acquired from the Pacific Gas and Electric Company.

The California Department of Water Resources (1990a) identified several generic problems facing rural water supply in the Sierra Nevada, which remain pertinent today:

- Rapid growth and development will burden existing water supplies and sewage treatment.
- Ground-water sources are not reliable in terms of quantity and quality.
- Water distribution systems are inefficient.
- Communities located on ridges are gravitationally disadvantaged.
- The best locations for impoundments have already been exploited by others.
- The revenue base is not sufficient to support water facilities at low rates per customer.
- Local funding sources are limited.
- Developing new water projects is economically and environmentally costly.
- Construction of new conveyance systems is expensive because of dispersed users and terrain.

Water companies and water-supply service districts in the Sierra Nevada vary in size from a few dozen customers to tens of thousands (Department of Water Resources 1983a; Harland Bartholomew et al. 1992). The nature of their sources, delivery and treatment systems, and demands are highly variable as well (e.g., Thornton 1992; Borcalli and Associates 1993). There are more than 160 separate water purveyors in Placer County alone (Placer County 1994). Water demands for individual households in the foothills have been estimated at 600–1,200 m^3/yr (0.5–1 AF/yr) (Page et al. 1984; Harland Bartholomew et al. 1992). Supplying new customers with existing water supplies may place current consumers at risk of shortfall during dry periods. Legislation was passed in California in 1995 (SB 901) to limit the ability of cities and counties to allow new developments unless local water purveyors certify that adequate water supplies exist for both present and expected residents. Sources of water for large proposed developments in the foothills, such as Yosemite Estates near Sonora, Las Mariposas near Mariposa, and Promontory near Placerville, are uncertain. Excessive water withdrawals from local streams can threaten recreational fisheries that form part of the economic base supporting the communities seeking the extra water for more development (Kattelmann and Dawson 1994). Development of additional water supplies is likely to become increasingly costly in both financial and environmental terms.

The projected demand for additional water in the foothills in the next few decades is staggering (see Duane 1996a). The Georgetown Divide Public Utilities District expects a 50% increase in water use in the next thirty years, and the El Dorado Irrigation District anticipates demand to double in the same period (Borcalli and Associates 1993). In Amador County, domestic water use was forecast to rise by between 2.6 times and 3.6 times between 1983 and 2020, depending on which population projections were used (Department of Water Resources 1990a). Tuolumne County expects to add 14,000 people in the next twenty years, who will need about 8.6 million m^3 (7,000 AF) of water each year to support them. The largest expected increase has been postulated for the service area of the Nevada Irrigation District, where annual domestic use could go from about 15 million m^3 (12,000 AF) to about 40 million m^3 (33,000 AF) between 1992 and 2010 (Harland Bartholomew et al. 1992). Nevada County is in perhaps the best position to meet the expected demands. The Nevada Irrigation District currently has rights to more water than is used and has a vast base of agricultural use that is expected to decline. Calaveras County also appears to have a relatively secure water supply. Some streams that have been dewatered below diversions may receive some flow for instream needs as older contracts expire and are reviewed. Other regions must find new sources of water and presumably will want to build new storage facilities or acquire existing hydroelectric projects.

SKI AREAS

As the major industrial/commercial development in the higher-elevation parts of the Sierra Nevada, ski areas have generated public concern about impacts of the resorts on water resources. Because of their extensive marketing campaigns and their location along the major access roads of the range, one could get the impression that there are ski areas all over the Sierra Nevada. However, the twenty-five alpine resorts occupy a tiny fraction of the land area in the mountain range. Only a few of the larger resorts, such as Squaw Valley, Alpine Meadows, Heavenly Valley, and Kirkwood, occupy a major proportion of the immediate watershed they are situated in. Most of the more significant impacts of ski resort development are associated with base facilities, roads, and parking lots. Such facilities are usually located in a valley bottom and impact streams and wetlands. For example, the parking lot of Boreal Ridge converted a large subalpine meadow into an expanse of impermeable asphalt and channelized Castle Creek. Because of the need for flat ground at the base of ski areas, many streams have been rerouted or even put underground. Access roads are often located in riparian zones. Runoff from roads and parking lots is usually polluted. The base facilities, lodging, and recreational residences generate substantial amounts of wastewater, which has usually required a local sewage treatment plant. Sewage system failures occasionally occur under harsh winter conditions. Most of the impacts of small urban areas can be applied to resort development. Ensuring an adequate water supply for all uses (residential, commercial, snow making, landscaping, erosion control plantings, and golf courses) for a major resort community can be problematic even in prolific source areas of snowmelt runoff (Kattelmann and Dawson 1994).

Vegetation Conversion

Impacts related to the ski slopes themselves begin with tree removal for runs and lift access. Such clearing constitutes a permanent conversion of vegetation type, as opposed to forest harvesting, which implies hydrologic recovery. When runs are cleared, deep-rooted trees are replaced with shallow-rooted grasses, greatly reducing evapotranspiration and increasing soil moisture storage. Because ski runs are typically oriented down the fall line, there is little opportunity for trees downslope to use the extra soil water in transit. Type conversion on ski runs can generate at least 7–15 cm (3–6 in) per unit area harvested of additional stream flow (Hornbeck and Stuart 1976; Huntley 1992). In some situations, subsurface drainage pipes and new surface channels may need to be installed to accommodate the additional water and avoid saturated conditions that could lead to mass movement. In some areas, there is extensive excavation and shaping of the natural terrain. Maintenance of sufficient ground coverage for adequate erosion control may require artificial irrigation and fertilizers in summer. Excessive use of fertilizers can contribute to high nitrate levels in local ground water (Goldman et al. 1984). Erosion from ski areas seems to be fairly well controlled and largely in compliance with rules from the regional water quality control boards, especially in the Lahontan Region. General construction always has the potential for accelerating erosion, but best management practices for minimizing soil loss at ski areas are becoming fairly thorough (i.e., Calaveras Ranger District 1991). In general, ski areas can afford to invest in erosion control and slope stability techniques that are not possible outside of major engineering projects. Somewhat analogous to abandoned mines, abandoned ski areas have potential for severe erosion problems, as occurred at Pla-Vada, where high sediment loads from gullies on the ski slopes damaged fish habitat in the nearby South Yuba River (California Division of Soil Conservation 1971a).

Snow Compaction

Grooming operations, avalanche control, and skiing compact the snow and move some of it downhill. A study of effects of compacted snow near Donner Summit found that snow water equivalence on the narrow ski runs was up to 50% greater than that on adjacent uncompacted slopes and that ski runs remained snow covered for up to two weeks longer than adjacent uncompacted slopes (Kattelmann 1985). Chemicals, such as ammonium nitrate, sodium chloride, and calcium chloride, have been used at a few ski areas to prepare race courses and improve skiing conditions in spring and summer. In general, only small areas are treated with relatively small quantities of chemicals. Degradation of water quality is a concern and has been reported in Europe.

Artificial Snow

Snow making has become widespread among the ski areas of the Sierra Nevada because skier demand seems to be greatest in November and December, when natural snow cover may be marginal. Artificial snow is produced by mixing water and air under high pressure through a nozzle. The sudden expansion cools the water and forms ice particles, which provide a reasonably good skiing surface and base for natural snow. Typical depths of applied water range from 20 to 50 cm (8–20 in), so the area covered is the main determinant of the total volume of water used. Most of the water used is returned to the stream it was originally withdrawn from, but delayed by 5 to 8 months. Evaporative losses of 2%–5% occur at the nozzle, and sublimation losses from artificial snow on the ground (and not covered by natural snow) range from 10 to 50 mm depending on how long the snow is exposed (Eisel et al. 1988; Huntley 1992). If water diversions for snow making will seriously deplete stream flows during the low-flow part of the year, off-channel storage capturing one season's snowmelt runoff to artificially initiate the following season's snow cover, such as is practiced at Mammoth Mountain, may be warranted.

Prospects for Expansion

Despite seemingly flat skier demand and the failure of about a quarter of the nation's smaller ski areas in the past decade, future prospects appear good enough to the ski industry to add additional capacity (see Duane 1996b). For example, revenues at Northstar-at-Tahoe and Sierra-at-Tahoe grew by 4% in the first quarter of 1995. Major expansion occurred at Sugar Bowl in 1994 and is planned at Kirkwood. Squaw Valley has proposed construction of a new base complex and has plans for year-round skiing. An entirely new ski area has been approved by the Forest Service in the Mammoth Lakes area, but $50 million in financing for construction may be difficult to obtain. Various large-scale development schemes have been proposed in the Royal Gorge/Devil's Peak region near Soda Springs.

INTERPRETATIONS

Historic and Current Conditions

The most significant impacts to the hydrologic system of the Sierra Nevada started almost immediately with the boom in Euro-American entry into the mountains during the gold rush. The effects of riverbed and hydraulic mining were devastating to the rivers of the western slope. Substantial recovery of the obvious features of channel morphology and riparian vegetation provides the appearance of natural rivers, but the aquatic and riparian ecosystems may remain quite simplified compared to the pre-1848 conditions. However, we will never know. As mining subsided, water development quickly took its place as an overwhelming, though less intensively destructive, impact. Although the severity of overgrazing may have peaked between about 1890 and 1930, continued grazing pressure has prevented thorough recovery of many degraded streams, and some (e.g., North Fork Feather River) continue to deteriorate. Early logging probably denuded larger expanses of the Sierra Nevada but may have applied less intense hydrologic disturbance to the soil than the road-building and tractor-skidding era that began after World War II. The various impacts of residential development have accelerated in the past decade. Impacts of fire and the legacy of fire suppression have yet to play out.

Water resources of the Sierra Nevada are highly controlled for various social purposes. That management causes the greatest current impacts to other social and ecological uses. The degree of alteration of natural stream flows generally increases in the downstream direction where the water passes through or is withdrawn by successive projects. However, the amount of unregulated flow from hydrologically intact tributaries also increases downstream, helping to "dilute" the effects of river engineering, at least until the big dams on the main rivers are reached. The dilution effect is also important in ameliorating changes in land use, which are most obvious close to their point of occurrence. The addition of water from relatively unimpacted watersheds helps offset the adverse cumulative impacts of assorted disturbances. Downstream of points of diversion, streams may lack the capacity to transport natural and accelerated sediment yields. Overall, water quality remains high compared with other rivers of the United States, but many problems exist locally. Alterations in the flow regime may be the most widespread degradation of water quality.

The primary trends related to water resource conditions at the scale of the entire mountain range have been recovery from gold mining and increasing regulation of stream flow via water developments. Both trends have diminished through time after the main geomorphic adjustments to mining debris and early dams occurred and the optimum dam sites and water rights were acquired and developed. Impacts from forest road building may have peaked as most of the potential road network would seem to be in place (see McGurk and Davis 1996); however, the high road density in some catchments ensures continued sediment yields at high rates. Impacts from residential road building and associated activities seem to keep increasing as the development of the foothills continues. An important question for planners is how to meet growing water demand while minimizing the environmental impacts of additional water development.

Some Implications

The overwhelming impacts on the water-resource system of the Sierra Nevada are those that directly modify the flow regime and the channel. Landscape impacts are secondary in those river basins of the Sierra Nevada with substantial water development. Even among land-use activities, those adjacent to or near a channel have far greater impacts than activities distant from water. Improvement of land-management practices and restoration should focus on issues closest to the streams if amelioration of aquatic impacts is a primary goal. Similarly, stream health will not suffer so much if disturbances are positioned well away from streams. Throughout this discussion of stream health, there is a presumption that fully functional aquatic ecosystems are inherently valuable and that attributes of streams beneficial to aquatic life (natural flow regime, low sediment transport, stable channel, good chemical quality, etc.) are also beneficial to the human uses of water. Aquatic ecosystems in headwater catchments are at greatest risk of damage from land disturbance. Combined effects of water engineering and land management may be particularly harmful to some aquatic communities.

Time Significance

Although there is no absolute urgency in changing the way society treats streams, the sooner damaging practices are improved or avoided, the sooner streams will benefit. Taking care of existing problems sooner rather than later and avoiding new mistakes will reduce the total impact (e.g., less sediment into stream pools or reservoirs) and may cost far less in the long run. Lake Tahoe is the best example of a system that needs urgent attention to slow the rate of deterioration of a particular resource or value (i.e., lake clarity). At Lake Tahoe, human activities have clearly altered a critical component of the ecosystem (nutrient cycling), and because the lake is extraordinarily sensitive in that regard, ecological responses are obvious and rapid. Although there are few real parallels to the Tahoe situation in terms of urgency, there are many other important problems to address. For example, reducing streambank erosion in the North Fork Feather River is clearly an important goal. As long as comprehensive action is delayed, productive alluvial land will continue to be lost, streams will continue to carry high sediment loads, and downstream reservoirs will continue to fill with sediment at unnaturally high rates. The most urgent problems are those where continued degradation could be irreversible or extremely expensive to mitigate if allowed to persist.

Perceptions

The adverse impacts of water management are probably overlooked by the public at large because of the obvious, personal benefits of that management. Perception of water-related impacts from residential development in the foothills is probably mixed depending on whether the individual has lived in a foothill community for decades, is a newcomer, relies on continued growth for personal income, or does not live in the area. Water-related problems associated with land management may be perceived by some people as more serious than they really are because of the visual impacts and media attention. The degree of destruction and subsequent recovery from placer and hydraulic mining are not widely recognized.

Gaps

Obviously, the operational difficulties lie in site-specific details. The assessment in this chapter is a very broad treatment of an entire mountain range. The problems are in particular streams. Every watershed has a story that is critical to its own stream. Management is conducted at that scale. The broad generalizations made here only provide the regional context for individual catchments and streams. The absence of information on recent sediment yields and limited stream-flow records from unregulated streams prevent any quantitative conclusions about how much land management has altered yields of water and sediments in the Sierra Nevada. Impacts on aquatic biota are also difficult to quantify because of scarce baseline data (see Erman 1996; Moyle 1996; Moyle and Randall 1996; Moyle et al. 1996).

Ecosystem Sustainability and Management

The physical recovery of streams from the gold mining era demonstrates the resiliency of rivers. Although recovery is probably to a more simplified state, with some lingering attributes of the original disturbance, this recovery illustrates an inherent long-term sustainability of the fluvial and aquatic systems, even in response to catastrophic impacts. On land, vegetation seems to reclaim favorable sites (i.e., riparian areas, north-facing slopes) very quickly after fire or logging. Drier sites and areas with special problems may require active intervention to reestablish ground cover in the short term or the avoidance of such sites in the first place. Recovery of other ecosystem properties and processes following disturbance requires much more time and possibly some management if we are impatient with nature's schedule. Ecosystem management must avoid impeding natural recovery processes after a fire or other disturbance, incorporate such processes in planning management programs, and augment them when necessary to accelerate ecological change in a desired direction, especially on difficult sites.

Remaining Questions

Among many important questions about hydrologic impacts of land management, three stand out:

1. How much has sediment yield been altered by human activities?
2. How much has the stream-flow regime (annual water yield, peak flows, low flows) been altered?

3. How do changes in water quantity and quality relate to declines in aquatic biota?

Reservoir sediment surveys on a 10- to 20-year cycle could be very informative about the first unknown. Establishment of a long-term network of stream gauges in strategic locations, such as actively managed headwater catchments, could be very informative about the magnitude of changes in hydrologic processes resulting from changes in land use. The present network informs us about water management and needs to be supplemented to inform us about land management. An aquatic research program, such as that suggested by Naiman et al. (1995), would help address many of the gaps in knowledge regarding streams of the Sierra Nevada.

CONCLUSIONS

From a hydrologic perspective, the Sierra Nevada seems to be functioning adequately as the preeminent water source for California society, agriculture, and industry. However, the hydrotechnical structures that facilitate exploitation of streams for social uses create the greatest impacts to those very uses as well as to aquatic ecosystems. This highly managed water system has created artificial patterns of stream flow in the lower reaches of most rivers and their principal tributaries. There are not many opportunities for further development of water resources in the mountain range, given existing infrastructure and water rights. Financing additions to community water supplies without subsidies from hydroelectric generation will be difficult at best. Existing ground-water development near foothill communities limits the availability of subsurface water as a dependable supply for future growth. The managed flows and physical barriers to movement of water, sediment, and biota have substantially altered aquatic and riparian ecosystems to something other than natural.

Compared with the intentional alteration of stream flow through water management, hydrologic side effects of changes in land use are difficult to measure but are still believed to be significant. Major changes in water and sediment regimes have not been observed in the main rivers and their larger tributaries as a result of shifts in land use. There may be a signal, but it is not obvious or well quantified. Hydrologic changes resulting from land management are most likely to be found in headwater areas, where a large fraction of the catchment has been affected. Diversion of water from a stream will limit transport of excess sediment loads and thereby compound the impacts of land disturbance. Roads are believed to have increased sediment yields substantially, but the inferred changes have not been measured in the Sierra Nevada. Overgrazing has probably altered channel conditions extensively, but the scarcity of ungrazed reference sites limits researchers' ability to quantify impacts. Rapid expansion of foothill communities has theoretically altered runoff and erosion processes enough to cause noticeable impacts in downstream channels, but quantitative and documentary evidence outside the Tahoe basin is lacking. Conversion of forestlands to roads associated with timber harvesting may have increased annual water yields and peak flows somewhat at the small watershed scale. However, decades of successful fire suppression may have increased evapotranspiration relative to a pre-1850 fire regime and partially compensated for the flow increases attributed to roads and harvests. The offsetting magnitudes of either impact cannot be quantified at this time. The legacy of fire suppression creates substantial risks of serious hydrologic impacts from potential conflagrations.

Overall, chemical water quality remains high, but water cannot be considered pristine. Because of widespread biological contamination, surface waters throughout the range cannot be assumed to be drinkable. A few local problems are very serious: Lake Tahoe, some abandoned mines, and some communities. Quality of receiving waters from the larger cities in the foothills has been degraded. These aquatic systems are not as sensitive to nutrient loading as Lake Tahoe. Excessive sediment production is the most widespread non-point-source problem, but its extent and severity are unknown. Studies in other areas suggest that roads are the overwhelming source of sediments that end up in wildland streams. Disturbance in and near stream channels generates the vast majority of sediment transported by the streams. Existing information about sediment yields in Sierra Nevada rivers is largely obsolete, and new reservoir sediment surveys are necessary to determine whether changing land use has accelerated sedimentation in the past few decades. Because of the importance of flowing water in diluting and dispersing pollution, alteration of stream flow by storage and diversion may be the fundamental water quality problem in the Sierra Nevada.

MANAGEMENT IMPLICATIONS

The ecological health of a stream is affected by all activities in its watershed. Those activities that directly control the flow regime or occur within the riparian zone usually have the greatest potential impacts. Changes in reservoir management practices may offer the best hope for improving aquatic ecosystems where they are known to be influenced by artificial flow regimes. In general terms, some shifts back toward a natural hydrograph, such as seasonally fluctuating flows, occasional flushing flows, maintenance of adequate low flows, or whatever is appropriate to a particular situation, will be beneficial to the local biota. Simply maintaining constant minimum flows is rarely sufficient. Stream habitat conditions and aquatic biota have developed in response to a highly variable natural flow regime. Restoring some aspects of that variability in managed streams should have ecological benefits in most cases. In some cases, changes in reservoir releases to benefit downstream organisms and water quality may have few adverse impacts on economics of the project. In other cases, there may be substantial costs, which may not be justified for the intended benefits. The tradeoffs between in-stream impacts and operational impacts must be carefully evaluated in the context of each water project, the watershed it is located in, and the ultimate downstream uses. There could be continued realignments in water rights as a result of application of the public trust doctrine, hydropower relicensing requirements, and regulation of reservoir releases by the regional water quality control boards for water quality management. The State Water Resources Control Board could ease legal and administrative matters by improving their water-rights database. An efficient, geographically referenced database for water rights could allow examination of in-stream flow conditions in a cumulative context for each stream and river system. Designation of additional wild and scenic rivers could help maintain ecological values of selected segments.

Major reconstruction of smaller dams to allow sediment pass-through under high-flow conditions could help restore some semblance of a natural sediment regime to many streams. Such work is a serious challenge in hydraulic engineering and reservoir management, but it would be an important contribution of technology to restoring natural processes in the managed rivers of the Sierra Nevada. Provision for flushing flows is particularly important where land disturbance may have augmented natural sedimentation and regulated flows encourage sediment deposition.

Recent actions by the State of California and the U.S. Forest Service to use watersheds as a geographic basis for planning and management are encouraging. As local agencies and citizens begin to incorporate a watershed basis into their own activities, overall conservation of aquatic resources should greatly improve. Continued public education about basic watershed concepts can only help. Application of watershed analysis methodologies developed in the Pacific Northwest (e.g., Montgomery et al. 1995) to the Sierra Nevada would be a worthwhile step toward improved management of wildlands at the landscape scale (see Berg et al. 1996). Watershed analysis can provide managers with better information about resource capabilities, existing problems, and sensitive areas before plans are made and projects are proposed. This analysis develops a logical foundation for decision making.

Reform of the 1872 Mining Act and greater application of California's Surface Mining and Reclamation Act to smaller claims could improve many isolated problems associated with mining and prevent future adverse impacts. Laws relating to liability that prevent rehabilitation of abandoned mines need to be modified, and funding must be generated to clean up problem mines. Mining of sand and gravel in streams of the Sierra Nevada should be directed toward reservoir deltas, despite the increase in transportation cost. Public agencies should set an example by using reservoir sediments as a source of aggregate whenever possible and avoiding chemical use in surface waters. The Department of Fish and Game (which administers streambed alteration agreements) might be able to negotiate agreements between reservoir operators and aggregate miners and users.

Modern information on sediment yields is needed to determine whether sedimentation has increased as a result of land-management activities. The California Department of Water Resources' Division of Dam Safety, the U.S. Geological Survey, and the U.S. Natural Resources Conservation Service might be the appropriate agencies to cooperatively administer a program of routine reservoir sediment surveys.

More efficient means of monitoring hydrologic impacts from land-management activities need to be explored at the operational field level and at the institutional level. Existing programs do not seem to provide the information necessary to evaluate how stream-flow regimes or water quality attributes are changing as a result of changes in land use. Current monitoring is also not adequate to determine whether restoration activities, including postfire treatments, are effective and appropriate. Maintenance and improvement of the snow survey, snow sensor, and climate station network is essential to management of water resources and detection of climate trends. Basic data collection programs to generate stream-flow, water quality, and climate information need to have long-term support to be worthwhile.

Now that the forest road network is largely complete, more attention should be focused on maintenance, relocation, upgrading, and decommissioning of roads by the engineering staffs of the national forests. Resource staffs have already identified many of the specific problems in the road network that need attention. Road construction budgets have been high in the past, and adequate funding is necessary to maintain, improve, and reduce the existing road system to minimize its aquatic impacts.

As foothill communities continue to grow, conversion from individual septic systems (and individual wells, in some cases) to community systems will be necessary to avoid cumulative impacts on local water quality. Construction of treatment facilities and collector systems is extremely expensive, especially where houses are far apart. The issue of who pays for such improvements is problematic. The community systems would not be necessary if not for the growth in potential pollution sources. At the same time, a community system is necessary because the capacity of the soil and ground-water system to treat household sewage is at or near its limit. Except for the service area of the Nevada Irrigation District, Calaveras County Water District, and a few others, foothill communities will need to develop major new sources of water or drastically reduce existing demand if they wish to continue their growth. Unless hydroelectric generating capacity is added when developing new sources of supply, project financing and end-user water rates may be serious constraints on new projects. Purchase of existing facilities (now largely owned by the Pacific Gas and Electric Company) by small communities and water agencies may be an increasing trend in attempts to augment community water supplies.

With all changes in land use and other disturbances, proximity to streams is a critical influence on the aquatic impacts of the activity. Simply minimizing disturbance of vegetation and soils near streams and conscientious application of best management practices for erosion control have the potential for reducing sediment problems. This locational emphasis is especially important with respect to grazing. Overgrazed riparian areas need substantial rest to adequately recover from past problems. Allowing such recovery means minimizing the presence of livestock and other disturbances in riparian zones on a continuing basis.

Management of forest fuels to reduce the risk of catastrophic fire must include thorough consideration of aquatic impacts and mitigation measures. If a major program of fuels treatment is started, a dedicated team of soil scientists, hydrologists, and aquatic ecologists should be involved in the planning and execution of such a program on local administrative units. A team of specialists, on either a zone or regional level, is also needed to monitor and evaluate the long-term effects of postfire treatments. Their experience could develop a rational set of best management practices for dealing with burned landscapes.

Prevention of further degradation and correction of existing water-related problems is expensive, as the Lake Tahoe experience has demonstrated. Rehabilitation of forest roads and restoration of degraded streams will require substantial investment. The forests of the Sierra Nevada contain three resources of substantial economic value to society: water, timber, and recreational opportunities. Some of their value in the marketplace could be returned to their sources and used to improve the conditions favorable to their production. Because the benefits of water from the Sierra Nevada contribute to so many aspects of California's economy, creative means of reinvesting a portion of those benefits into the watersheds need to be explored.

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Status of Riparian Habitat

ABSTRACT

Despite their ecological importance, riparian areas in the Sierra Nevada have been the subject of very little research and no systematic data collection at a scale adequate to directly evaluate the status of the resource over the entire range. In this chapter, we review the functioning and ecological importance of riparian areas, the effects of human activities on riparian areas, and the extent of these effects in the Sierra Nevada. Riparian areas in the Sierra Nevada have been directly removed or have had their functions impaired by gold mining, gravel mining, hydroelectric development, land clearance and diversions of water for irrigation, land drainage, phreatophyte removal programs, timber harvest, construction of roads and railroads, urbanization, livestock grazing, and groundwater abstraction. From a GIS (Geographic Information Systems) analysis of road influence on streams, we calculated the percentage of 100 by 100 m pixels containing streams that also contained a road, which we designated as the Road Influence Index (RII). RII values, a measure of stream length with a road within 100 m, range from 2% to 33%, with a median value of 14% for the Sierra Nevada. Aerial photographic analysis indicated that 121 of 130 study watersheds displayed obvious gaps in the riparian corridor, primarily from road and railroad crossings, timber harvesting, clearing of private lots, dewatering by dams and diversions, and livestock grazing. Examination of 1:100,000-scale topographic maps for the entire Sierra Nevada showed more than 150 gaps over 0.5 km long created by reservoirs and at least 1,000 km of riparian corridor eliminated by reservoir inundation. Management strategies to minimize effects on the riparian zone include buffer strips, flushing flows, and restoration of riparian habitat. Streamside management zones or land-use buffers may be used to filter pollutants and sediment from upland runoff and to provide adequate recruitment of organic matter to the channel. Deliberate release of high flows from reservoirs (flushing flows) may be used to mimic the effects of natural floods in maintaining bed substrate and active channel width. Riparian vegetation can also be replanted in sites from which it has been cleared.

INTRODUCTION

Riparian habitats are among the most ecologically productive and diverse terrestrial environments, by virtue of an extensive land-water ecotone, the diversity of physical environments resulting from moisture gradients, and a mosaic of habitats created by dynamic river changes (Naiman et al. 1993). Moreover, the importance of the physical and biological interchanges between aquatic and riparian habitats is increasingly recognized, so any consideration of aquatic habitat quality must account for the riparian conditions so influential upon the channel itself (Gregory et al. 1991). Riparian habitats are especially important in semiarid regions, where the availability of moisture and a cool, shaded microclimate gives these habitats an ecological importance disproportionate to their areal extent. For example, in the Inyo National Forest, riparian areas constitute less than 0.4% of the land area but are essential for at least one phase of life for about 75% of local wildlife species (Kondolf et al. 1987b). In this forest, many recreational activities for its annual seven million visitors are also concentrated in riparian zones (Federal Energy Regulatory Commission 1986). Of the total 401 Sierran species of mammals, birds, reptiles, and amphibians combined, 21% (84 species) depend on the riparian area near water, and of course many more use it occasionally or regularly to find food, water, and shelter (Graber 1996). Nearly one-quarter (24%) of

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

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those dependent on the riparian community area are at risk of extinction (Graber 1996).

Until the 1960s, the ecological importance of riparian areas in mountain regions was largely undescribed in the scientific literature (Kauffman 1988). In the Sierra Nevada, little has been published on riparian areas per se, although the importance of riparian areas is implied by the habitat descriptions for many species. Interest in riparian areas in California has been growing over the past two decades, but most research has focused on the Central Valley or Coast Ranges. For example, in the proceedings of a conference held in 1988 on riparian habitat in California (Abell 1989), 46 papers concerned the Central Valley or Coast Range riparian systems and only 17 concerned Sierra Nevada (mostly eastern or southern) riparian systems.

In the 1980s, a proliferation of proposals for small hydroelectric developments generated a number of mostly site-specific studies on the environmental effects of proposed hydroelectric projects (e.g., Taylor 1983; Harris et al. 1987; Kondolf et al. 1987b; Jones and Stokes Associates 1989; Smith et al. 1989; Nachlinger et al. 1989; Leighton and Risser 1989; Hicks 1995).

Land-management agencies have conducted studies of riparian areas as a component of other assessments or planning studies. Mono County is conducting detailed mapping of wetlands, including riparian areas (R. Curry, University of California, Santa Cruz, communication with R. Kattelmann, 1995). Riparian areas along streams tributary to Mono Lake have been studied by a National Academy of Sciences committee (National Research Council 1987), on behalf of parties to litigation over flow requirements for resident trout (Stromberg and Patten 1990), in support of a water rights adjudication (Stine 1991; State Water Resources Control Board 1994), and in related studies (Kondolf and Vorster 1993). The California Tahoe Conservancy is attempting to evaluate the health of riparian vegetation along streams tributary to Lake Tahoe using remotely sensed data and field observations (Manley 1995). In many cases, these site-specific studies have been sufficiently well funded and implemented that they provide valuable insights into the physical and ecological processes controlling the distribution and functioning of riparian vegetation. However, most have been concentrated in the Mono Basin, Lake Tahoe, or Kern River regions.

Attempts at a broader scale assessment of riparian conditions have been undertaken by the Bureau of Land Management (Myers 1987) and the U.S. Forest Service (e.g., U.S. Forest Service 1995). Unfortunately, inconsistencies in data collection, analysis, and reporting have inhibited the compilation of these various data into a coherent assessment of riparian conditions across the entire range. Moreover, many assessments, such as those undertaken by the national forests, have been conducted without the benefit of peer review of procedures or results, and some are based largely on subjective judgments of channel stability by nongeomorphologists and thus contribute little to a scientifically based understanding of the status of riparian systems in the Sierra Nevada.

METHODS AND SCOPE

This chapter provides an overview of the functioning and ecological importance of riparian areas, the effects of human activities on riparian areas, and the extent of these impacts in the Sierra Nevada, based largely on a more detailed report (Kattelmann and Embury 1996). Although the continuity of riparian corridors was assessed from aerial photography of a sample of river systems over the entire Sierra Nevada, the effects of human activities upon riparian areas are merely inferred from the extent of human activities known to affect the extent or functioning of riparian vegetation. Direct measurement of riparian condition over a region as large as the Sierra Nevada was beyond the scope of this study.

A literature review was conducted on the ecological role of riparian areas, the physical conditions on which they depend, and the effect of human activities on riparian areas in general. These extensive references are summarized in tables (reviewed in more detail in Kattelmann and Embury 1996), and are generally not repeated in the text. Literature documenting physical and biological aspects of riparian areas in the Sierra Nevada was also reviewed, but this literature is relatively modest and does not reflect the full range of conditions found in the Sierra Nevada.

The courses of all rivers and streams appearing on U.S. Geological Survey (USGS) 1:100,000 topographic maps were examined to identify gaps greater than 0.5 km (0.3 mi) in the riparian corridor produced by reservoirs. The total length of inundated channel was estimated by assuming straight-line distances for channels under existing reservoirs.

More than 9,500 km (5,900 mi) of river and stream channel was examined on aerial photographs to identify gaps in the riparian corridor. Out of 694 Sierra Nevada Calwater Super-Planning Watersheds, as designated by the California Department of Forestry and Fire Protection (1996), 130 were selected for aerial photographic study. All blue-line channels appearing on USGS 1:100,000 scale maps were examined. Aerial photographs for most national forests were taken in 1991–93, but coverage for other watersheds dates back as far as 1981. Details of coverage, scale, and methods of assessment are presented in Kattelmann and Embury 1996. Aerial photographs provide little or no information on the condition of riparian vegetation below the canopy, and the small scale of the photos used limited the utility of this analysis to an assessment of canopy continuity (riparian fragmentation).

A more systematic analysis was conducted using a geographic information system (GIS) developed for the Sierra Nevada Ecosystem Project. For 141 Calwater Hydrologic Subareas (California Department of Forestry and Fire Protection

1996) in the Sierra Nevada study region (four subareas were omitted because they were reservoirs), the number of pixels (each 100 m by 100 m, or 1 ha [2.47 acres]) in which a road occurs was counted, and the number of pixels with a stream was counted. Sources of the digital road information were the U.S. Forest Service road layer of "system roads" for areas inside proclaimed boundaries of national forests and the Teale data center (1:100,000) for areas outside the proclaimed boundaries. Of the total number of pixels with streams, the percentage that also had roads was calculated, a statistic that can be restated as the percentage of stream length with a road within 100 m (328 ft) of the channel—a gross measure of the potential impact of roads upon streams. These percentages for each watershed were compiled for the entire Sierra Nevada and for the northern (north of Interstate 80), central (Merced River basin to I-80), southern (south of Merced River basin), and eastern (east of the divide, excluding Lake Tahoe) Sierra Nevada. For each data set, percentile values (10th, 25th, 50th, 75th, and 90th percentiles) were determined and box-and-whisker plots (modified from Tukey 1977) were generated to display the spread of values among individual watersheds.

We also convened a group of scientists familiar with riparian management issues in the Sierra Nevada to review an early draft of Kattelmann and Embury 1996, to discuss the topic, to contribute ideas and other published research to the review, and to consider how best to approach this broad subject. The comments received from this group were extremely helpful in preparing this chapter.

FINDINGS

Ecological Role of Riparian Areas

Riparian vegetation is vegetation associated with rivers, streams, and other aquatic systems (lakes, springs, seeps, wet meadows). The term has been variously defined, from meanings that restrict the term to vegetation occurring on the river banks (as implied by the Latin root ripa, bank) to more inclusive definitions that encompass floodplain and terrace vegetation as well. Bottomland vegetation is another term for the latter, more inclusive definition of riparian vegetation (e.g., Hupp 1986). Water-dependent vegetation found at springs and seeps is often referred to as riparian despite the lack of association with a stream or river. Our review and assessment has concentrated on the riparian areas associated with running water. Riparian vegetation is also distinguished as obligate, for species found only in riparian areas, and facultative, for species that commonly occur in riparian areas but that also occur in upland environments.

Individual riparian species are adapted to a range of conditions within the riparian zone, along gradients of water table depth, soil moisture, and frequency of disturbance. Characteristics typical of obligate riparian vegetation are dependence on a high water table, tolerance to inundation and soil anoxia, tolerance to physical damage from floods, tolerance to burial by sediment, ability to colonize flood-scoured surfaces or fresh deposits, and ability to colonize and grow in substrates with few soil nutrients. The relative importance of these characteristics varies with the river system. In the Sierra Nevada, dependence on high water tables and ability to survive physical damage from high-velocity flood flows are important characteristics of riparian vegetation, whereas along the coastal plain rivers of southeastern North America, tolerance of prolonged inundation is more important.

The ecological importance of riparian areas derives from a range of attributes, such as moisture availability, structural complexity, linear continuity (for migration corridors), distinct microclimate (cooler in summer, protected in winter), diverse food resources (terrestrial and aquatic), and influence on aquatic habitat (table 36.1). Riparian vegetation has a greater influence on channel processes and aquatic habitat in smaller channels than in larger ones. The effect of roots in stabilizing banks, the role of large woody debris in channel processes, the importance of terrestrial food sources as opposed to autochthonous (within channel) food production, and the shading effect of bank vegetation are all relatively more important in small channels (Vannote et al. 1980).

Geomorphic and hydrologic processes and conditions important to riparian ecology include flood inundation, the physical effects of high-velocity flood flows, stream-groundwater interactions, and the extent and texture of alluvium and adjacent hill-slope soils (table 36.2). The relative importance of these physical controls, like that of vegetation, differs among riparian systems. Altering these controls can be expected to alter the distribution and structure of riparian vegetation.

Human Impacts on Riparian Areas

A wide range of human activities can affect riparian areas, either by direct removal of riparian vegetation or by altering the factors controlling the distribution and structure of riparian vegetation (table 36.3). The following paragraphs briefly review these impacts and consider their relative importance in the Sierra Nevada.

Gold mining has numerous effects on riparian vegetation, including the destruction of riparian bottomland forests for gold dredging, the damming and diversion of rivers, and increased sediment yield from hydraulic mining. Gold mining was extensive in the Sierra Nevada beginning in about 1850 (see Beesley 1996). To provide water and pressure for hydraulic mining, ambitious water diversion projects were undertaken, resulting in the dewatering of some reaches and the creation of new riparian habitats along artificial canals. The mining itself released more than 42 million m^3 (46 million yards^3) of sediment into steep canyons, burying existing vegetation before being flushed downstream for deposition in channels and on floodplains of rivers in the Central Valley

TABLE 36.1

Ecological attributes of riparian areas.

General Attribute	Specific Attributes	References
Moisture availability	Shallow water table supports phreatophytes	California State Lands Commission 1993
	Evapotranspiration, shading increase humidity	
	Moist environments for amphibians, reptiles	Reynolds et al. 1993; Jennings 1996
Structural complexity	Vegetation provides cover for wildlife, birds	
	Multiple plant canopies create multiple niches	Krzysik 1990
	Seasonal changes in deciduous vegetation	Reynolds et al. 1993
Periodic disturbance	Floods disrupt existing organisms, providing opportunities for pioneer species	Resh et al. 1988; Sparks et al. 1990; Junk et al.1989
Linear nature	Edge effect: terrestrial-aquatic ecotone	Schimer and Zalewski 1992
	Riparian zones serve as wildlife migration corridors	Thomas et al. 1979
Food resources	Diverse vegetation yields diverse foods	Cross 1988
	Diverse habitat harbors diverse prey	Raedeke et al. 1988
	Open water available for wildlife	
Microclimate	Shaded, cool, moist in summer	Raedeke et al. 1988
	Protected in winter: overwintering habitat	
Influences on aquatic habitat	Shading moderates water temperatures	Brown 1969
	Shading moderates algal growth	
	Plant materials and insects fall into stream, adding chemical energy and nitrogen	Cummins et al. 1989; Knight and Bottorff 1984
	Riparian zone “buffers” stream from upland	Erman and Mahoney 1983; Mahoney and Erman 1984
	Riparian vegetation stabilizes stream banks	Kondolf and Curry 1986

and San Francisco Bay (Gilbert 1917; Mount 1995). Along the Yuba River above Marysville, the “debris plain” built of these sediments exceeds 64 km^2 (40 mi^2) in area.

A later phase of mining involved dredgers. These reworked the natural floodplains or hydraulic mining debris and left behind elongated mounds of tailings, which are still largely unvegetated because their surfaces consist of open cobbles in which plants cannot become established. The dredgers required extensive, deep, relatively flat deposits to work, so they were concentrated in the lower Central Valley reaches of western Sierra Nevada rivers.

Gravel mining for construction aggregate from river channels and floodplains results in the direct removal of riparian vegetation for the creation of process yards, haul roads, and pits. Indirect effects of in-channel extraction typically include channel incision, which propagates both upstream and downstream, lowering the alluvial water table and inducing channel instability.

Gravel mining for construction aggregate is the largest mining industry in the state (see Diggles et al. 1996). More than 100 million metric tons are produced annually, virtually all from river channels and floodplains. Large gravel depos-

TABLE 36.2

Selected geomorphic and hydrologic processes in riparian areas.

Process	Physical Effect	Ecological Consequence	Reference
Flooding			
Inundation	Soil anoxia	Selects for plants tolerant of anoxia	Walters et al. 1980; Gill 1970
	Saturation of soil	Increases soil moisture	
High-velocity flow	Scour of seedlings	Prevents establishment of woody vegetation in channel	
	Physical damage to plants	Selects for tolerant plants	Sigafoos 1964
	Bank erosion and undercutting of mature vegetation	Creates new habitats for colonization	
Deposition	Burial of plants	Selects for tolerant plants	Sigafoos 1964
	Sand-gravel bar deposition	Selects for plants capable of colonizing sandy substrates	
	Fine-grained overbank deposition	Provides silty substrates	
Stream-Groundwater Interactions			
Drainage from hill slope	Maintains high water table	Supports vegetation independent of streamflow	
Bank storage	Recharges alluvial water table	Supports vegetation	Kondolf et al. 1987a
	Maintains base flow	Provides water downstream	

TABLE 36.3

Human activities, physical effects, and ecological consequences in riparian areas.

Activity and Potential Direct Physical Effects	Potential Ecological Consequences	References
Gold Mining		
Former floodplain forests reworked by placer mining into unvegetated dredger tailings	Riparian vegetation removed and replaced with unvegetated gravel	Clark 1970
Rivers and streams dammed and diverted through canals	Water stress in dewatered reaches, riparian vegetation established along canals and ditches	Averill 1946; Pagenhart 1969
Increased sediment from hydraulic mining debris leads to aggradation of sand and gravel in valley bottoms	Burial of existing vegetation	Gilbert 1917
Continued erosion from hydraulic mine sites	Elevated fine sediment loads affect aquatic biota	Marchetti 1994
Gravel Mining		
Direct removal of vegetation for gravel yards, processing plants, haul roads, pits	Riparian vegetation replaced by roads and industrial land use	Poulin et al. 1994
Mining-induced channel incision lowers alluvial water table	Increased mortality, decreased growth rate and crown volume in woody riparian vegetation	Kondolf 1994b; Scott et al. in press
Mining-induced channel instability results in increased bank erosion	Erosion of banks supporting riparian vegetation	Todd 1989
Mining tops of gravel bars (“skimming”) lowers ground surface relative to water table	Riparian vegetation established in channel where water table was formerly too deep	Kondolf and Matthews 1993
Dams		
Reduced flood flows lead to reduced rate of channel migration	Reduced diversity of riparian habitats	Johnson 1992, 1994; Ligon et al. 1995; Hesse and Sheets 1993
Reduced flood flows eliminate frequent scour of active channel	Riparian vegetation encroaches into active channel	Williams and Wolman 1984; Bergman and Sullivan 1963; Brothers 1984
Increased base flows and raised alluvial water table	Waterlogging of vegetation	Parrish and Matthews 1993
Base flows reduced or eliminated, stream dries up	Riparian vegetation severely stressed or dies	Kondolf and Vorster 1993; Stine et al. 1984
Trapping of bedload sediments behind dam, release of sediment-starved water, channel incision	Alluvial water table drops and overbank flooding is less frequent due to channel incision	Williams and Wolman 1984
Reservoirs drown existing vegetation, fluctuating water levels may limit establishment of new vegetation along margins	Longitudinal continuity of riparian corridor interrupted	Hagan and Roberts 1973
Hydroelectric Generation		
Rivers and streams dammed and diverted through canals	Water stress in dewatered reaches, riparian vegetation established along canals and ditches	Harris et al. 1987; Kondolf et al. 1987b
Hydroelectric dams and associated canals, penstocks, power-houses, and access roads constructed within riparian zone	Riparian vegetation removed and replaced with roads and structures	Federal Energy Regulatory Commission 1986
Flow fluctuates rapidly to generate peak hydroelectric power	Rapid stage changes can lead to increased bank erosion	
Irrigation		
Water diverted from streams	Water stress in dewatered reaches, riparian vegetation established along canals and ditches	Erman 1992
Irrigation water may infiltrate, recharging groundwater	Excess irrigation water may support vegetation	Kondolf and Vorster 1993
Land Drainage		
Alluvial water table lowered by land drainage	Riparian plants desiccated	Hughes 1934
Land Clearance for Agriculture		
Removal of floodplain forest	Riparian vegetation removed and replaced with agricultural land	Katibah et al. 1984
Phreatophyte Removal		
Removal of riparian vegetation	Riparian vegetation removed, may require herbicides to prevent regrowth	Dunford and Fletcher 1947; Biswell 1989
Navigation		
Channel dredged, resulting in incision	Alluvial water table drops and overbank flooding is less frequent due to channel incision	Brookes 1988
Channel straightened and stabilized	Length, complexity, and dynamic nature of channel reduced	Brookes 1988
Timber Harvest		
Harvest of timber in riparian areas, removal of trees for logging road construction	Direct loss of large trees in riparian areas, reduction in structural complexity, elimination of supply of large woody debris to channel	Gregory et al. 1991; Maser and Sedell 1994
Log transport on rivers erodes banks, simplifies channel geometry	Habitat complexity reduced	Sedell and Luchessa 1981
Removal of timber on hill slopes, resulting in increased peak runoff and erosion	Bank erosion, conversion of vegetated bottomland into open gravel-bed channel	Lyons and Beschta 1983; Grant 1988

continued

TABLE 36.3 (continued)

Activity and Potential Direct Physical Effects	Potential Ecological Consequences	References
Road and Railroad Construction		
Railroads and highways often follow rivers, built along banks of river	Riparian habitat replaced by railroad or highway for long distances along one bank	Scheidt 1967
Railroads and highways cross rivers	Continuity of riparian corridor interrupted by gaps at crossings	Furniss et al. 1991
Failure of roads and culverts delivers sediment to channel	Sediment reduces invertebrate habitat and populations	Erman et al. 1977
Urbanization		
Settlement along riverbanks and on bottomlands	Riparian habitat replaced by urban infrastructure	Medina 1990
Increased impervious surface upstream increases peak runoff, induces channel widening, incision	Water table may fall with incising channel, resulting in moisture stress to vegetation	Dunne and Leopold 1978; Booth 1990
Land drainage to make land suitable for development	Desiccation of riparian vegetation	National Research Council 1992
Channel relocation or channelization for flood control	Engineered channel margins rarely provide suitable conditions for establishment of riparian vegetation	Brookes 1988
Grazing		
Livestock trample and compact banks	Prevent establishment of vegetation, crush amphibians	Armour et al. 1991; Chaney et al 1990; Jennings 1996
Livestock hooves chisel banks	Destroy existing vegetation, destroy undercut banks, contribute to channel widening	USFS 1995; Overton et al. 1994; Kondolf 1994c
Livestock browse seedlings	Recruitment of young woody riparian plants prevented	Platts 1991
Removal of vegetation and compaction in watershed leads increased peak runoff and erosion, possibly to decreased to base flow	Erosion of banks supporting riparian vegetation	Behnke and Raleigh 1979; Platts 1991; Dudley and Dietrich 1995
Previously listed factors lead to incision of channels, especially in meadows	Water table drops, desiccating wetland species	Odion et al. 1990
Lack of bank vegetation and undercut banks, channel widening,and higher water temperatures	Reduced fish populations, reduced invertebrate populations	Behnke and Raleigh 1979; Armour et al. 1991; Herbst and Knapp 1995
Groundwater Abstraction		
Groundwater pumping lowers alluvial water table	Water table may fall below root zone of riparian plants, inducing moisture stress or death	Kondolf and Curry 1986
Recreation		
Heavy foot traffic tramples vegetation, compacts soil, and physically damages bank	Loss of riparian vegetation, creation of bare banks prone to erosion	Liddle 1975; Madej et al. 1994
Trails (foot, horse, bicycle, motorcycle) often follow streams	Riparian vegetation removed and replaced by trail; continuity of riparian corridor interrupted at crossings	Holmes 1979; Lemons 1979

its tend to occur in wider alluvial reaches, and thus mining is concentrated in foothill and valley reaches of Sierran rivers, although mines are also active along the upper reaches of the Feather and Yuba Rivers (California State Lands Commission 1993) and the American River (Kondolf and Matthews 1993).

Dams have direct effects from the permanently removal of riparian habitat to construct roads, penstocks, powerhouses, canals, and dams. Reservoirs drown existing riparian vegetation, and fluctuating water levels usually prevent the establishment of comparable new vegetation stands along reservoir margins. Thus, reservoirs constitute significant gaps in the riparian corridors. The largest reservoirs are located in the foothills, but reservoirs large enough to constitute significant gaps occur at virtually all elevations, as reflected in plots of reservoirs by elevation for the Sacramento and San Joaquin River basins (figures 36.1 and 36.2). Maps of reservoir numbers and capacity by watershed reflect the widespread occurrence of reservoirs throughout the range, with greater capacity in the central Sierra Nevada (figure 36.3).

Indirect effects of dams derive from changes in the flow regime and sediment load on downstream channels. Reduction in floods leads to reduced rates of channel migration (which in turn reduces the diversity of riparian habitats) and to the encroachment of vegetation into (and thus the narrowing of) the active channel. Most vegetation encroachment and channel narrowing in Sierran rivers has been reported below large reservoirs in the foothills (Pelzman 1973), whose storage is adequate to substantially reduce flood flows. Large reservoirs are less common but do occur at higher elevations. Most have not been studied, but many would likely evince encroachment and narrowing downstream, as observed on the North Fork Kings River (Taylor and Davilla 1985).

By storing water during winter and spring for subsequent release, reservoirs can increase base flows, which can, in turn, waterlog riparian vegetation accustomed to well-drained conditions in late summer and fall. Summer base flows on the North Fork Stanislaus River have increased tenfold as a result of storage in a hydroelectric project, and mortality of many riparian trees has been predicted (Parrish and Matthews 1993). Where reservoir water is exported from the basin, base flows can be reduced. On Rush Creek, the principal tributary to Mono Lake, no regular base flow releases were made from

Grant Lake Reservoir from 1941 to 1981, and a massive die-off of woody riparian vegetation ensued (Stine et al. 1984).

Reservoirs also trap the coarser (sand and gravel) portion of the sediment load and some fraction of the suspended load (depending upon the capacity of the reservoir relative to inflow). As a result, reservoir releases are typically sediment starved—they have the energy to transport sediment but are deprived of this load. As a result they tend to erode their bed and banks (Williams and Wolman 1984). If the channel incises, the alluvial water table will probably drop, resulting in moisture stress for the riparian vegetation adapted to the previous water table.

Hydroelectric generation entails most of the effects of dams where storage is involved, but has a somewhat different suite of effects if the project involves diversion but no storage—a run-of-the-river project (figure 36.4). Small diversions are common in the Sierra Nevada, either for small run-of-the-river projects, or for seasonal diversion via tunnels into storage reservoirs in adjacent drainages (see Kattelmann 1996).

Irrigation usually involves storage reservoirs so that water is available during the growing season. Thus, irrigation projects typically involve many of the same effects as those described for dams, and because they cause a net decrease in river flow, irrigation projects dewater river reaches. Small fish can be pulled into unscreened diversions and killed when they are discharged onto agricultural fields. Excess irrigation water can support riparian vegetation in artificially created wetlands, fed either by surface flows or groundwater recharged by excess irrigation waters. Along Rush Creek in Mono Basin, excess irrigation water infiltrated into permeable bedrock and reemerged downstream as springs. This process maintained high water tables, reestablished perennial flow, and thereby supported riparian vegetation even when diversion had completely dried the channel upstream (Kondolf and Vorster 1993). The combination of dams and diversions results in impacts in the majority of watersheds of the Sierra Nevada (figure 36.3d). Although few large dams are found in the northern region of the study area, this region has in general a higher density of diversions than other regions.

Most large irrigation storage reservoirs on Sierran rivers are in the foothills; irrigation diversion from Friant Dam and downstream diversions completely dries up the San Joaquin River annually at Gravelly Ford. Seasonal diversions without storage were used to irrigate farmland on the Bishop Creek alluvial fan by Native Americans and subsequent European settlers. These irrigation canals now support lush riparian vegetation (Federal Energy Regulatory Commission 1986). A seasonal irrigation diversion on the Little Truckee River reduced flows and resulted in channel widening downstream (Erman 1992).

Land drainage (usually for agriculture or urbanization) results in desiccation of wetland plants. Drainage of former meadows has been common around Lake Tahoe, resulting in loss of many riparian plants and invasion by upland species. Probably the most widespread land drainage in the Sierra Nevada has been in wet meadows, which have been drained deliberately (documented as early as the 1870s, as in the dynamiting of a moraine in Yosemite Valley by Galen Clark to drain upstream meadows) (Greene 1987) and inadvertently because of channel incision (generally attributed to effects of livestock grazing) (e.g., Odion et al. 1990).

Land clearance for agriculture has been most common in wide alluvial reaches in the foothills and Central Valley, where formerly extensive bottomland forests were cleared, leaving only a narrow band of riparian vegetation (if any) along the bank.

Removal of vegetation was undertaken in the southwestern United States, mostly on an experimental basis, to reduce water "losses" to evapotranspiration by phreatophytes. Although some phreatophytes were eliminated in the Sierra Nevada (Biswell 1989), the environmental impacts of this practice (Campbell 1970) are generally acknowledged to be too great to justify it. Nonetheless, an increased water yield anticipated as a result of forest harvesting (mostly upland) has been factored into the national forest planning process in California. The Sequoia National Forest attributed 30% of the "benefits" from its preferred alternative of the latest forest plan to the supposed value of increased water expected as a by-product of timber harvest (U.S. Forest Service 1988).

Navigation by large ships commonly requires channel dredging and straightening, mostly undertaken in lower, valley reaches of rivers, downstream of the study area.

Timber harvest affects riparian vegetation directly and indirectly. Riparian vegetation has been removed in harvests of bottomland forests, and the construction of logging roads along bottomlands replaces riparian vegetation with road surface. Past log drives down rivers resulted in extensive battering of banks, reducing habitat complexity along the water's edge. Removal of timber on hill slopes, along with road construction and skid trail compaction, typically results in increased peak runoff and increased erosion. These so-called cumulative effects can degrade aquatic habitat and can potentially lead to the erosion of banks supporting riparian vegetation and the conversion of well-vegetated valley bottoms into wide, open, gravel bed channels (Grant 1988; Lyons and Beschta 1983).

Timber harvest has been extensive in the Sierra Nevada. Riparian trees, notably giant sequoia and other old-growth stands on bottomlands of Sierran rivers have been harvested, directly affecting bank vegetation and aquatic habitat. Franklin and Fites-Kaufmann (1996) found that 95% of the 1,200 ha (3,000 acres) separately mapped as riparian hardwood forest type had no late successional/old growth characteristics left, although deep, inaccessible river canyons with other forest types contained some of best remaining examples of old growth. Given that average angular canopy densities (canopy measured at an angle that effectively blocks summer sun) of 75% were observed on unlogged first- and second-order channels in the northern Sierra Nevada (Erman et al. 1977), removal of riparian trees has a tremendous effect on aquatic habitat.

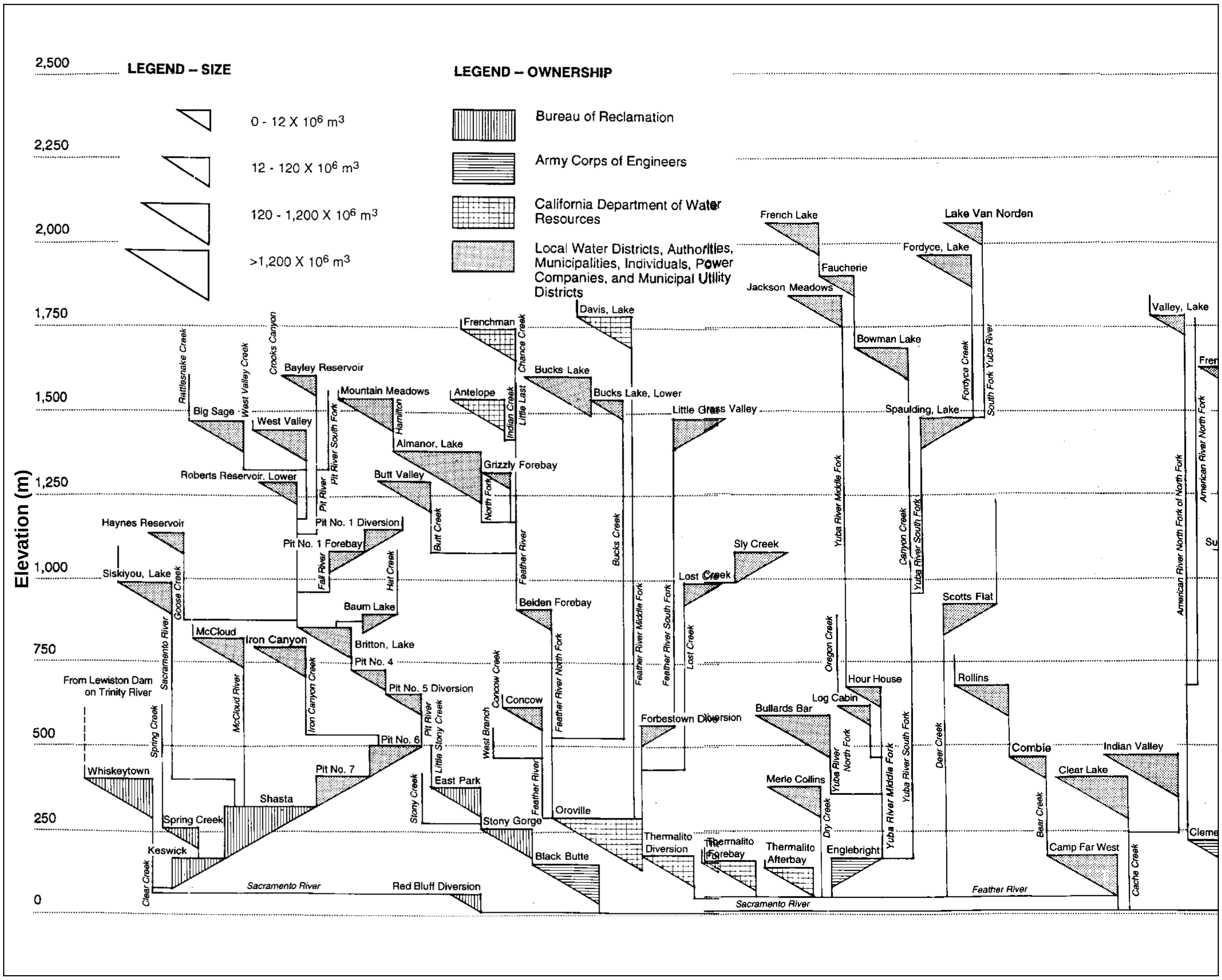


FIGURE 36.1

Schematic diagram of reservoirs in the Sacramento River basin, plotted by elevation. Reservoirs are included from two Coast Range drainages: Stony Creek (East Park, Stony Gorge, and Black Butte) and Putah Creek (Lake Berryessa and Solano Lake) and from the upper Sacramento River drainage that lies north of the Sierra Nevada. Otherwise, all reservoirs shown are in the Sierra Nevada or its foothills. (Adapted from a plot prepared by the California State Water Resources Control Board, Graphic Unit.)

The cumulative effects of timber harvest are widespread but poorly documented in the Sierra Nevada. Most of the timberlands in the Sierra Nevada lie within national forests. Despite this single ownership of large areas, and despite the mandate for the Forest Service (and other agencies) to analyze cumulative impacts of forest management activities, very little basic data collection on peak stream flow and sediment yield (the variables likely to be affected by timber harvest) is undertaken on the forests. Most field data collection and office analyses are apparently devoted to cumulative effects "assessment methods" (see Berg et al. 1996) that primarily involve office-based computations of such variables as area of road surface and timber harvest within a watershed to predict cumulative impacts. These computations of effects are not verified by actual field measurements of peak flow or sediment yield, and in some cases, the results of these "methods" have been contradicted by field observations of Forest Service biologists (Kondolf 1994a).

Railroads and roads commonly follow rivers, taking advantage of flat bottomland and linking riverside settlements. These railroads and roads (and the additional settlement generated along them) displace riparian vegetation on the floodplain. In narrow canyons with limited bottomland, roads and railroads are commonly located along the riverbank itself,

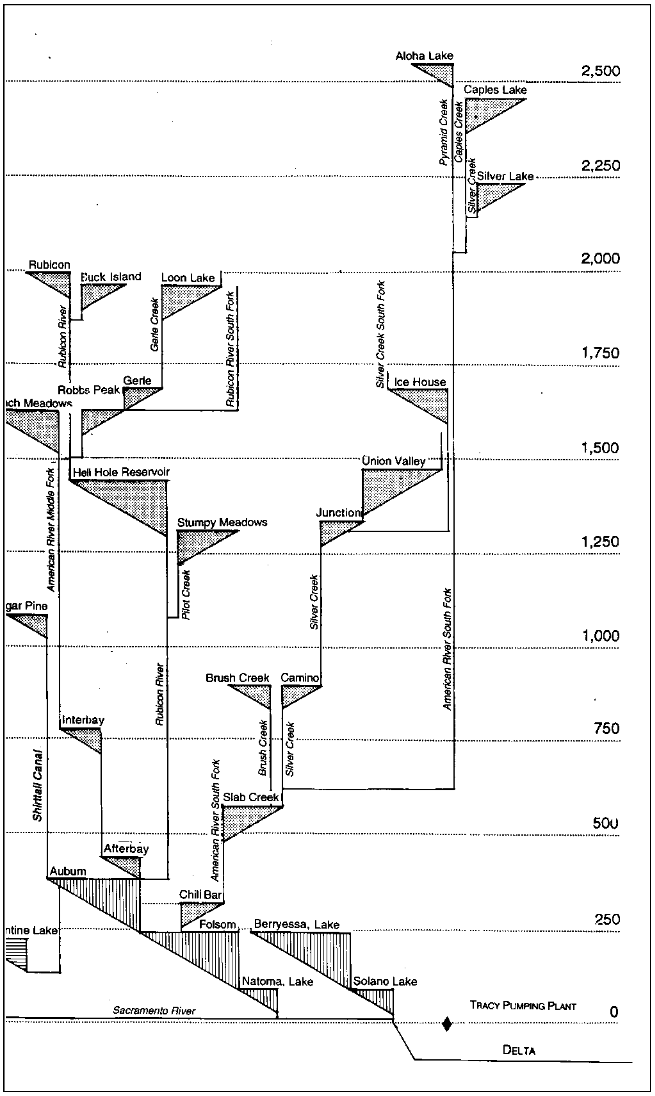


FIGURE 36.1 (continued)

replacing overhanging bank vegetation with riprap, which tends to narrow the channel with artificial fill. Even in the absence of these longitudinal impacts, the continuity of the riparian corridor is interrupted at each bridge crossing. Concentrated road runoff commonly carves gullies, and unpaved logging roads and their culvert crossings may wash out during storms, delivering pulses of sediment to the channel and degrading aquatic habitat and water quality.

Roads and railroads cross most of the Sierra Nevada, as indicated by the results of the GIS analysis of road influences on streams and by the aerial photographic analysis of riparian corridor gaps discussed later.

Urbanization has occurred historically along bottomlands because of the flat land, proximity to water, and connection to communication and trade routes that often followed rivers. When such urbanization occurs, buildings, streets, parking lots, and other urban infrastructure directly displace riparian vegetation. The impervious surfaces of rooftops and pavement result in greater surface runoff per unit of precipitation, increasing peak flows and commonly inducing channel incision, bank erosion, and a drop in the water table (which may desiccate riparian plants) (Dunne and Leopold 1978). Sites with shallow water tables may be deliberately drained to permit development, resulting in desiccation of riparian vegetation. As floodplains are urbanized, flood damages increase by virtue of the increased value of the flood-prone land (whether the floods be naturally occurring or exacerbated by land-use change). Thus, urbanization commonly creates a demand for flood control, which involves structural measures such as channelization or levee construction, in turn reducing or eliminating riparian habitat.

Since the 1940s, California has experienced tremendous population increases and corresponding urbanization. From 1980 to 1990, the state's population increased from 24 million to 30 million (California Department of Finance 1990). From 1984 to 1990, urban land area increased by 123,000 ha (303,810 acres) in the 42-county state Office of Land Conservation farmland mapping area (California Office of Land Conservation 1988, 1990, 1992). In the last two decades an increasing proportion of the population increase has been accommodated by dispersed "ranchette" settlement in rural counties of the Sierra Nevada (see Duane 1996). This increased urbanization pressure has effects on riparian areas ranging from direct urbanization (riparian areas are often preferred sites for ranchettes), to fragmentation by roads and other infrastructure to support urbanization in uplands, to hydrologic changes induced by urbanization in the watersheds, to increased use of riparian areas by humans and domestic pets.

Grazing by livestock results in the trampling and compaction of riparian areas, the direct destruction of bank vegetation by bank through the chiseling of banks by hooves, and the elimination of recruitment of young woody riparian plants through browsing (Armour et al. 1991; Platts 1991; Menke et al. 1996). The lack of bank vegetation eliminates shading and terrestrial food sources for the channel, and reduces the stability of the bank. Grazing throughout a watershed can increase peak runoff and erosion rates, leading to channel incision (and thus lowered alluvial water tables and desiccation of riparian plants), bank erosion, and increasing fine sediment content in channels (Behnke and Raleigh 1979). Grazing is commonly concentrated in riparian areas because of vegetation supported by the greater moisture availability and because the stream provides drinking water.

Grazing by livestock was virtually ubiquitous in the Sierra Nevada from the nineteenth century through 1930 (Vankat and Major 1978; McKelvey and Johnston 1992; Kinney 1996),

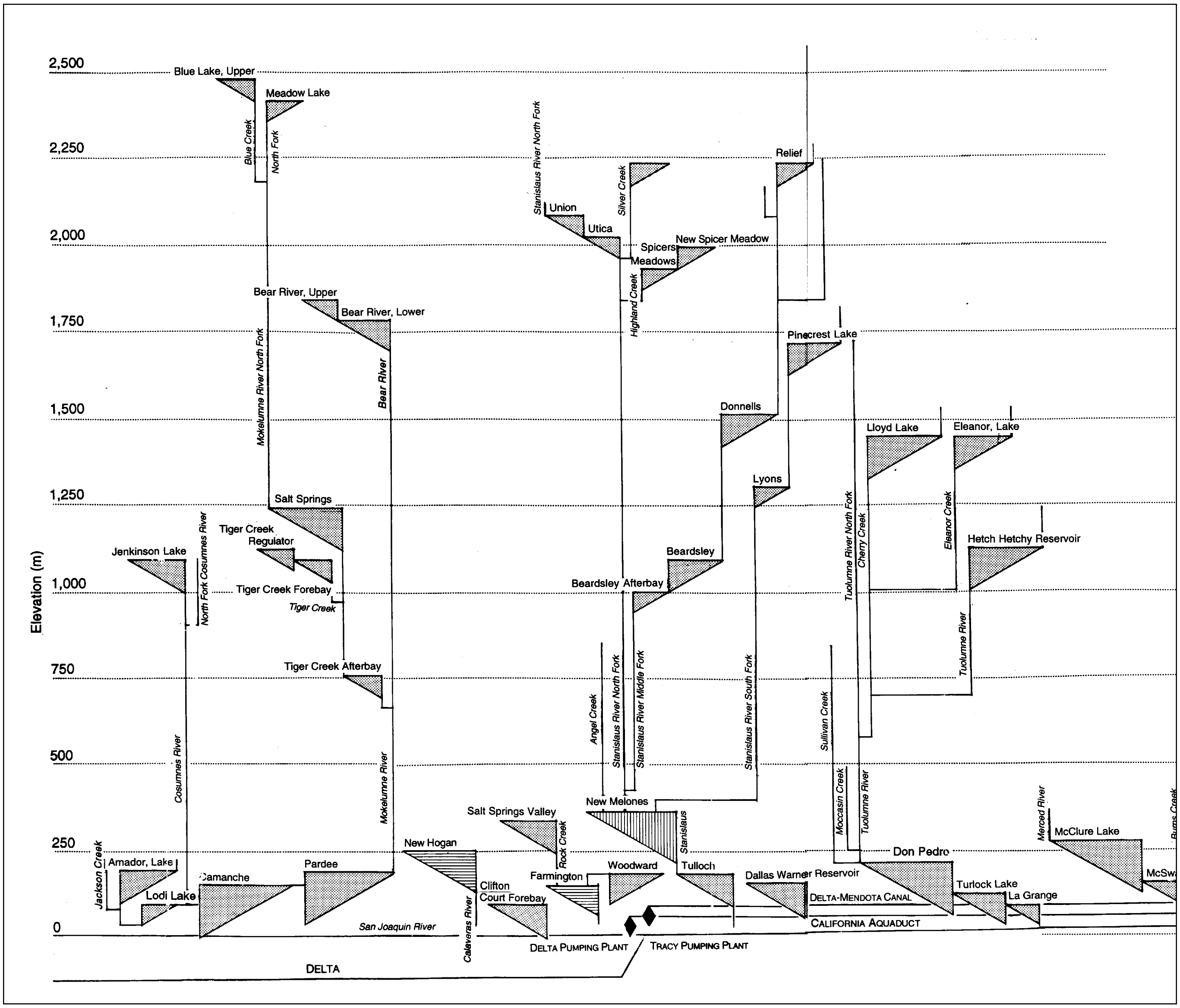


FIGURE 36.2

Schematic diagram of reservoirs in the San Joaquin River basin, plotted by elevation. Clifton Court forebay and four storage reservoirs in the Coast Ranges (San Luis, Little Panoche, O'Neil, and Los Banos) are included. Otherwise, all reservoirs shown are in the Sierra Nevada or its foothills. (Adapted from a plot prepared by the California State Water Resources Control Board, Graphic Unit.)

with heavy grazing even in many high-elevation meadows that remain inaccessible to vehicles today (Dudley and Embury 1995). As a result, channel incision and desiccation of meadow vegetation has been widespread in the Sierra Nevada. Grazing and its effects have been so pervasive and ubiquitous throughout the American West that virtually no unaffected "control" conditions exist for comparison, and what most people would regard as "natural" conditions are in fact influenced by historical (if not current) grazing (Elmore and Beschta 1987). Our best comparisons are derived from studies of vegetation and channel recovery when streams are excluded from grazing, but channel conditions may be slow to recover from grazing effects (Kondolf 1993).

Groundwater abstraction for municipal or agricultural use can reduce alluvial water tables, stressing or killing riparian vegetation (Kondolf and Curry 1986; Wright and Berrie 1987). Groundwater pumping in the Owens Valley has had the greatest documented effects on vegetation known in the Sierra Nevada region (Perkins et al. 1984; Groeneveld and Or 1994).

Recreation can affect riparian corridors through the concen-

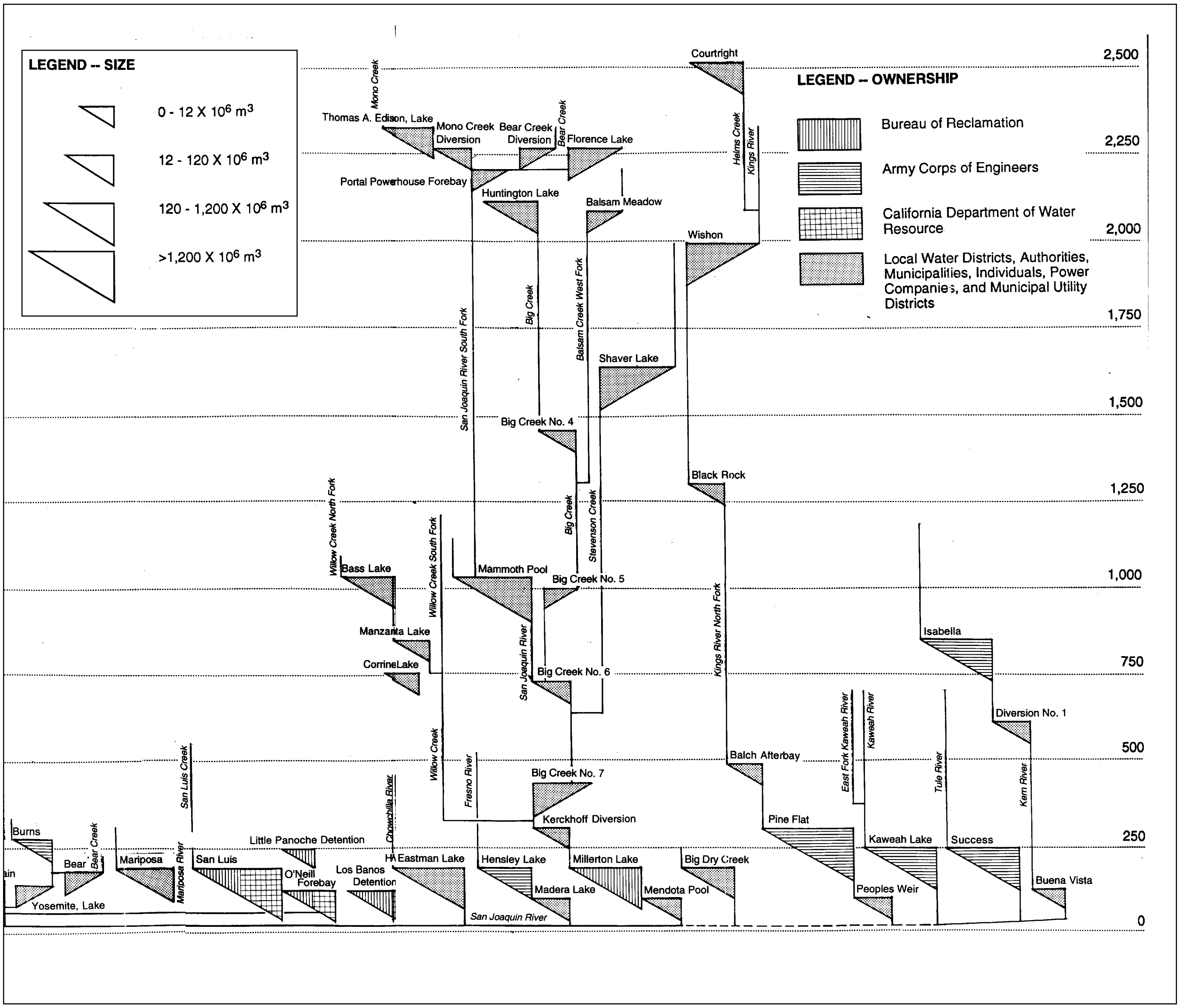


FIGURE 36.2 (continued)

tration of people along riverbanks: heavy foot traffic tramples vegetation, compacts soils, and can physically damage banks (Liddle 1975). Trails (foot, horse, bicycle, or motorcycle) replace riparian vegetation with pavement or bare, compacted earth and bring people into the riparian zone where they are then more likely to concentrate on banks, with the effects just described. Heavy concentration of anglers on the banks may have similar effects. These effects have been documented along the Merced River in Yosemite National Park (Madej et al. 1994) and are probably concentrated near popular campgrounds throughout the Sierra Nevada, but their overall extent has not been documented. Most national forest campgrounds in the Sierra Nevada are located in or near riparian areas.

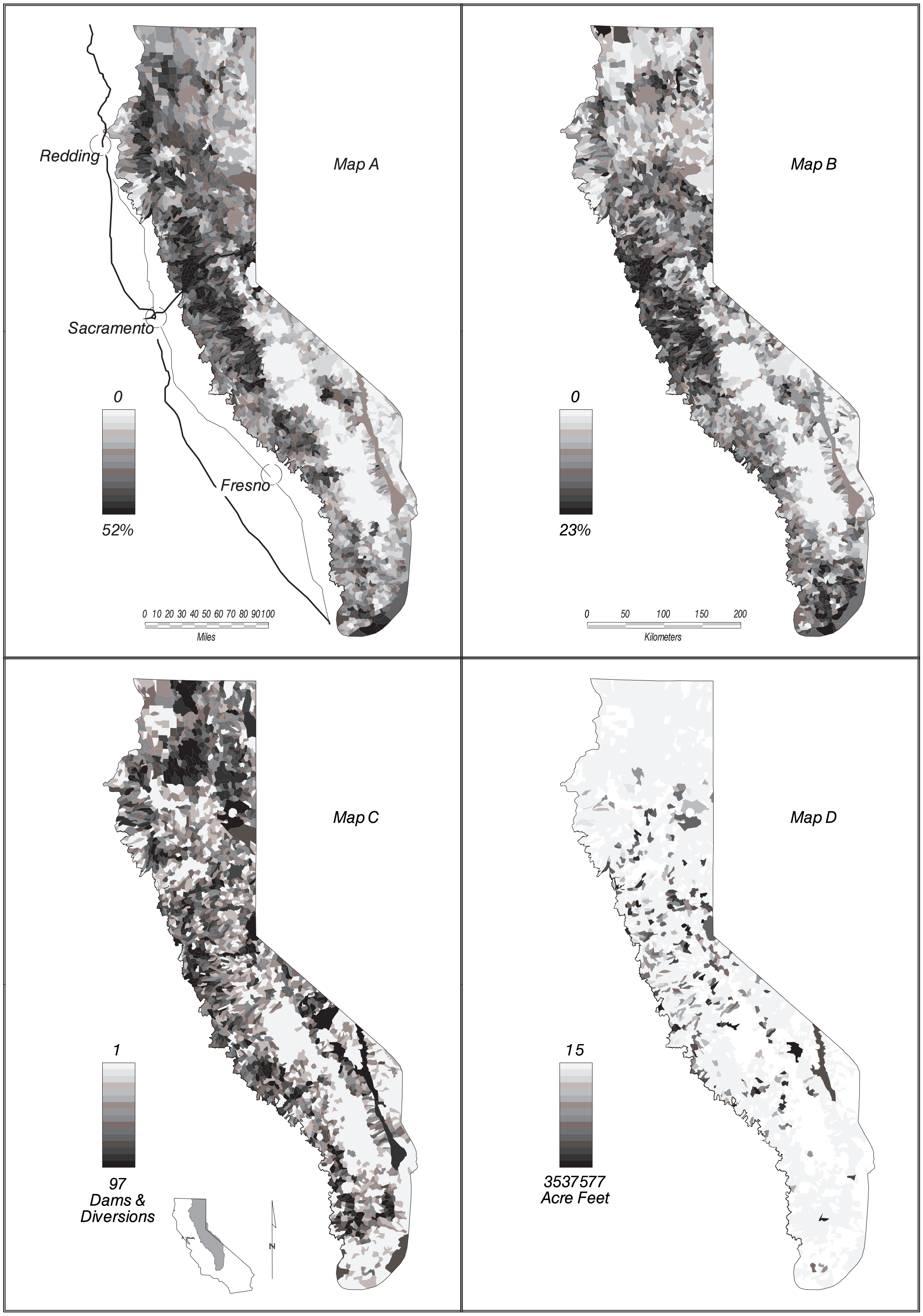


FIGURE 36.3

GIS plots of percentages of pixels (100 m x 100 m blocks) in each watershed that contain a road (map *a*), contain a road near a stream (map *b*), and contain a dam or diversion (map *c*). Map *d* shows dam capacity by watershed.

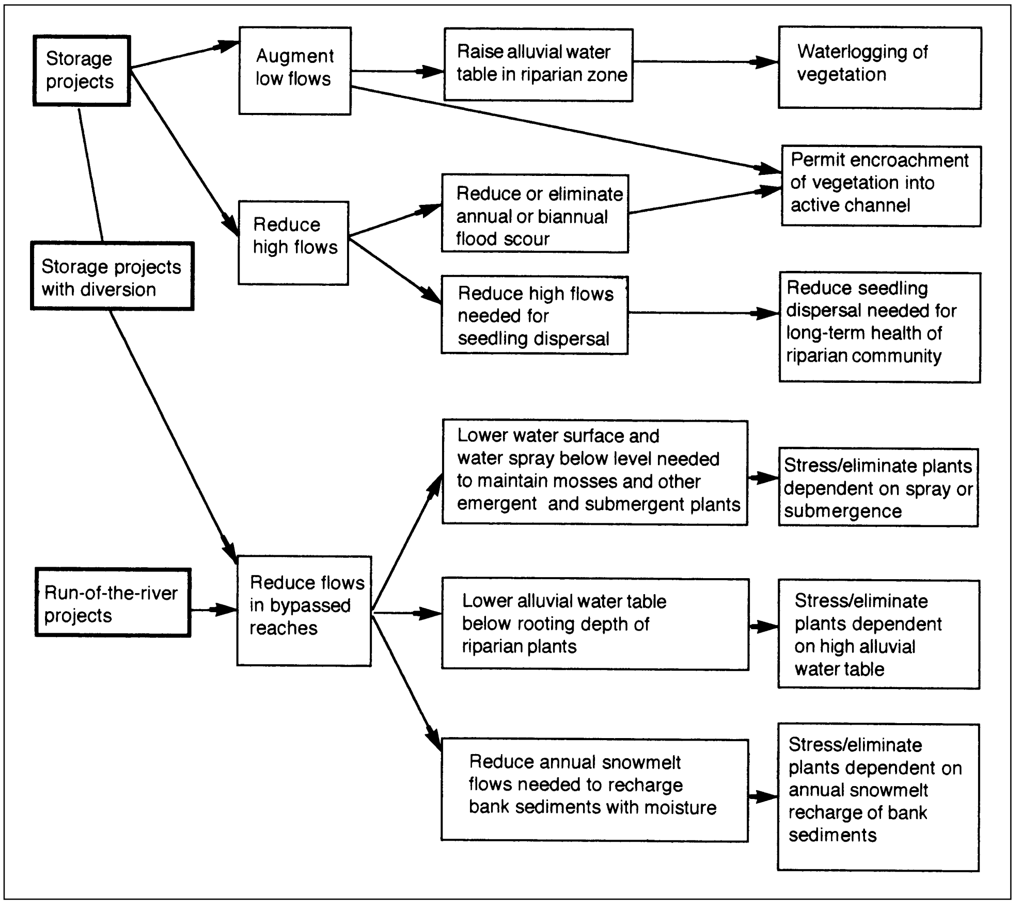


FIGURE 36.4

Effects of hydroelectric dams and diversions on riparian vegetation.

GIS ANALYSIS OF ROAD INFLUENCE ON STREAMS

An indication of the pervasiveness of road influence on Sierran rivers and streams is provided by the GIS analysis of 100 m by 100 m pixels in 141 watersheds (Calwater Hydrologic Subareas). In each watershed, the percentage of pixels with a road ranged from less than 0.6% to 31%, and the percentage with a stream ranged from 4% to 19% (figure 36.5). The results for roads are displayed for each watershed in figure 36.3a. When these patterns are overlaid, the more interesting result is obtained: the percentage of pixels with a stream that also contain a road, which we designate here as the Road Influence Index (RII) (figure 36.3b) The RII is a measure of the percentage of stream length with a road within 100 m. The RII ranges from 2% to 33%, with a median value of 14.1% (figure 36.5). The central 50% of the distribution (i.e., the 71 watersheds that fall in the center of the RII) have RII values between 10.8 and 17.4, and the central 80% have RII values between 8.7 and 21.3 (figure 36.5). Thus, in the vast majority (80%) of Sierra Nevada watersheds, 8% to 21% of stream reaches are potentially influenced by a road within 100 m. Additional detail, including values for this index, for thirty-three watersheds in the Eldorado National Forest is given in Costick 1996. He refers to this index as the percentage of roaded area inside a 100 m stream buffer.

The RIIs for watersheds in the northern Sierra Nevada (north of Interstate 80) are lower (median value 10) than those for watersheds in the central (median value 14), southern (median value 14), and eastern (median value 16) Sierra Nevada (figure 36.6).

The true values of RII are certainly higher than indicated here because the data sets used for roads were derived in large part from road maps, which do not show all roads. The total stream length would also be greater if smaller-scale maps (e.g., 1:24,000) were used to identify streams, as only larger streams are shown on the 1:100,000 scale maps.

Aerial Photograph and Map Analysis of Gaps in Riparian Corridors

Of the 130 Calwater Super-Planning Watersheds selected for assessment by aerial photography, 121 displayed obvious gaps in the riparian corridor. These gaps were caused primarily by road and railroad crossings, timber harvesting, clearing of private lots, dewatering by diversions and dams, and grazing.

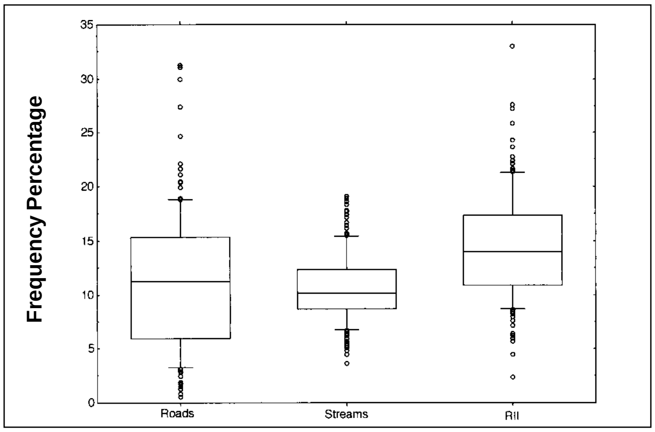


FIGURE 36.5

Box-and-whisker plots showing the percentage of pixels (100 m x 100 m) containing roads, the percentage of pixels containing streams, and the percentage of pixels containing streams that also contain roads in Sierra Nevada Calwater planning watersheds (*n*=141). The latter statistic can be restated as the percentage of streams with a road within 100 m of the channel, an index of the potential impact of roads upon streams, or Road Influence Index (RII).

The longest gaps (and thus perhaps the most influential ecologically) were created by reservoirs. USGS 1:100,000 topographic maps showed more than 150 reservoir gaps at least 0.5 km (0.3 mi) long. Highly developed basins such as the Feather and American Rivers had more than 20 reservoirs exceeding 0.5 km (0.3 mi) in length. The total length of riparian corridors inundated by reservoirs exceeds 1,000 km (600 mi).

MANAGEMENT IMPLICATIONS

Management Strategies

Management strategies can be used to minimize the impact of human activities on riparian areas or to restore ecological values of riparian areas. As described in preceding sections, human impacts to riparian systems have occurred by the direct removal or replacement of riparian vegetation or by the alteration of the physical conditions supporting riparian vegetation.

The most commonly applied, most straightforward, and probably most effective strategy is to define a riparian management zone or riparian buffer strip within which vegetation cannot be disturbed and ground compaction is avoided. This strategy serves not only to protect riparian vegetation for its own sake but also to maintain the beneficial influence of riparian vegetation upon aquatic habitat through shading, contribution of terrestrial food and nutrients, and filtering of sediments and pollutants from runoff flowing to the channel from surrounding uplands.

Because of the profound effect of dams in reducing natural high flows that support diverse assemblages of riparian vegetation, deliberate high flow releases are increasingly being required from reservoirs to maintain riparian habitat. Bottomland and bank areas that have been cleared for agricultural or urban uses are in some cases being restored to riparian habitat.

These management and restoration strategies are discussed in the following sections.

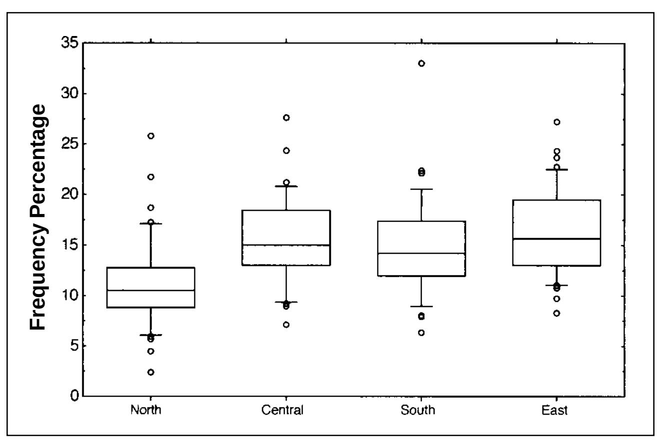
Land-use Buffers

The region near streams and other aquatic ecosystems, that is, the riparian region, is defined in three conceptually distinct ways: a transition or ecotone, a discrete habitat or community, and an area of special management or buffer between upslope land uses and the aquatic environment. No wonder that the terms and definitions vary with the context. Scientists and managers agree on the special nature of riparian areas. Both federal and California forest practice standards or rules specify restrictions and practices intended to protect streams and moderate their disturbance from land use (see Moyle et al. 1996). The main issue is not the special nature of riparian areas but rather how much area belongs in this category and what activities are acceptable. The ecological functions and process should be guides to use and protection.

Riparian ecological functions and physical processes take

FIGURE 36.6

Box-and-whisker plots showing the percentage of pixels (100 m x 100 m) with streams that also contain roads (Road Influence Index) in northern (north of Interstate 80, *n*=38), central (from Interstate 80 south through the Merced River Basin, *n*=29), southern (south of the Merced River Basin, *n*=35), and eastern (east of the divide, *n*=35) Sierra Nevada watersheds. This statistic can be restated as the percentage of streams with a road within 100 m of the channel, an index of the potential impact of roads upon streams.



place in three areas at varying distances from the aquatic system: a community area, an energy area, and a land-use influence area. The size of these areas depends on the local characteristics that define them. Any one of the areas may be larger than the others; in other words the three areas are nested within each other, but the order is determined by the characteristics that define them rather than an arbitrary hierarchy. One other fact is important in understanding the dimensions of the entire riparian area: it is not proportional to the size of the aquatic system. Ephemeral ponds, intermittent streams, and small springs are as important to the suite of species that depend upon them as large rivers are to another suite of species (see Erman 1996). Smaller aquatic systems in forested environments are dominated by the land system. Consequently, the impacts from changes in riparian forest structure and composition and from land disturbance result in major changes in the aquatic system (Erman et al. 1977; Minshall 1994).

The direction of state and federal protection of riparian areas has been based on broad classification of the aquatic system—presence of a life-form (fish-bearing vs. non-fish-bearing, for example), size (rivers vs. spring runs), or permanence (year-round stream flow in most years vs. temporary flow in most years). Classification of aquatic habitats for management in this way does not recognize the connected nature of aquatic systems (upstream-downstream), does not recognize the needs of riparian-dependent species, and cannot work for the protection of aquatic biodiversity (which is particular to the type of system), or properly assist in the management of interconnected land-water systems. Shifting to a recognition of the community, energy, and buffering requirements of riparian areas will aid in the protection and management of the entire riparian system.

The Community Area

For any aquatic habitat there is a suite of species that depend on the combination of land and water. Some spend most of their life in the water, some on the land. Most aquatic insects, for example, develop in water but spend a portion of the life cycle on land—feeding, mating, and resting (see Erman 1996). Alder and cottonwood trees are always associated with nearby water—a spring, a lake, a stream, or groundwater near the surface. From a knowledge of the habitat requirements and life connections of the dependent species, we should be able to define the general dimensions of this community area in the various regions and elevation zones of the Sierra. However, the exact requirements and hence the dimensions for many species are unknown. The water shrew (Sorex palustris) is likely confined to the virtual stream bank. Beavers (Castor canadensis) may move tens of meters from water to cut aspen or other trees, as well as cottonwood on relatively flat floodplains that extend more than 100 m from low-water channels. The California tiger salamander (Ambystoma californiense), which occurs in the foothills zone (see Jennings 1996), lives in terrestrial habitats near temporary and permanent water used for breeding. Adults migrate up to 129 m (423 ft) (average 36 m [118 ft]) and juveniles up to 57 m (187 ft) (average 26 m [85 ft]) between their breeding site and terrestrial burrows (Loredo et al. in press). Studies elsewhere on amphibians have found some species that live only in the cool, damp conditions near streams and up to several hundred meters from surface flow (Welsh 1993). Dramatic changes in riparian conditions due to the logging of forests near headwater streams have greatly reduced populations of riparian-dependent and terrestrial salamanders in the Appalachians (Petranka et al. 1994). Thus, to provide for the living requirements of those organisms dependent for their survival on the special conditions of the riparian area, the primary management should be maintenance of these conditions. Even the natural role of disturbance, documented in this chapter and others (see also Kattelmann and Embury 1996) does not require, in most situations, active restoration of the landscape in order to secure the habitat conditions necessary for the area.

The Energy Area

Major scientific understanding of the energy linkages between upstream and downstream (e.g., the river continuum concept, Vannote et al. 1980) and exchanges between the land area and aquatic systems has emerged in the last two decades (see reviews by Cummins et al. 1989; Carlson et al. 1991; Murphy and Meehan 1991). Riparian energy areas contribute a year-round supply of organic material that ranges from nearly the total supply of food at the base of the food chain (small forested streams and springs) to critical quality food (organic matter transported into larger streams from smaller upstream sources). Wind-blown seeds and leaves are a significant source of material entering meadow reaches with little forest canopy. The type of organic material is also important. Easily decomposed plant material (e.g., parts with a relatively low carbon-to-nitrogen ratio such as alder leaves), material that is slow to decompose (such as Douglas fir), as well as terrestrial insects carried in are needed to support an aquatic food web throughout the year. Flows of energy from the aquatic to surrounding terrestrial system (especially emerging insects) is also substantial (see Erman 1996) The surrounding riparian area also blocks energy from the sun and reradiation from the water (thus reducing temperature changes). And the role of large organic matter (trees, root-wads, debris dams) is of major importance to the structure and complexity of stream channels, to the routing of sediment, to the retention of nutrient supplies, and to the diversity of aquatic habitats. The dimensions of this region vary by the season (leaf fall of deciduous plants), by the hydrologic conditions (out-of-channel floods, size of stream), by the contributing area (large wood that can fall into the channel, plant parts and insects that blow in), and by the species mix (organic material breaks down and is useful as aquatic food at different times). A useful summary index of this area is the slope distance around the aquatic system equivalent to the height of the site potential tree (i.e., the height a mature tree can attain given the soil and other conditions at its location) (Chapel et al. 1992). For the Sierra Nevada, that height in many forest types is approximately 46 m (150 ft). However, the incorporation of wood and other organic material into streams will occur also during inundation of the floodplain. For larger streams in regions of gentle gradient, the width of a stream during major floods may extend much beyond 46 m.

The Riparian Buffer Area

The effects of land-use disturbance are reduced by keeping such activities at a distance from the aquatic system and by maintaining a buffer area capable of absorbing disturbance. The likelihood of disturbance to a stream from most land uses increases as a function of proximity to a stream, the steepness of surrounding hillsides, and the erodibility of soils. These relationships, as in many risk factors, are probably multiplicative and therefore a doubling of slope has more than twice the risk of disturbance to the stream (i.e., an exponential change). Current practice for designing buffer systems based on risk rely on classification of the aquatic system (as was mentioned earlier) and the creation of three or four categories of slope. As a consequence, a fixed width is chosen even though conditions on the land and requirements of the community would suggest a variable width (Bisson et al. 1987). We propose a more direct system for estimating a variable-width buffer system based on the community and energy area in combination with slope and other measurable risk factors.

For example, let us assume that a stream is in the mixed conifer zone. The determination of hillside slope can be made from topographic maps or from GIS. The SNEP GIS team has prepared a program that will calculate slope at 30 m (98.5 ft) increments along a stream channel. At each point, slope from five successive 30 m segments out from a channel are computed from the 30 m Digital Elevation Model. Slopes are then weighted 5, 4, 3, 2, 1, from closest to farthest away, and divided by 5 to produce a weighted average slope over the 150 m (slopes closest to the stream have the greatest effect on the average). Let's also assume that the stream has a community area defined by species as 110 ft (33.5 m) and an energy area that is 150 ft (46 m). Thus, a minimum region with maintenance of forest structure and minimal land disturbance is 150 ft for these two areas. This distance is then multiplied by the base of natural logs (*e*) raised to a power equal to 1+slope (in decimal form). If, for example, the slope were 25%, the equation would be

$$\text{Buffer width (ft)} = 150 * e^{(1+0.25)}$$

giving a value of 524 ft (160 m). If the average slope were 50%, the buffer would be 672 ft (205 m). In the first case, an additional 374 ft (114 m) of buffer would be needed. Soil erodibility, also available from soil maps and GIS, can be incorporated as the detachability value (see Costick 1996), and the exponent would be expanded to 1+slope+detachability – (slope * detachability). For example, if detachability were 0.30, the equation would be

$$\text{Buffer width (ft)} = 150 * e^{(1+0.25+0.30-0.075)}$$

giving a value of 656 ft (200 m). Extreme cases, when slope and detachability are both high, would result in even larger buffer zones, and as slope and detachability approach zero, buffer zones would become smaller—exactly the outcome common sense would indicate is appropriate. This additional area beyond 150 ft would not have the same land-use restrictions as the community and energy areas. Its purpose is to highlight a region in which probability of disturbance may affect the community or energy areas and the aquatic system. Silvicultural procedures should minimize soil disturbance and in general retain sufficient forest structure to ameliorate microclimate change within the community area and minimize the abrupt transition from the area upslope to the community area. Describing the buffer zone as a "probability of disturbance region" places the responsibility on managers for designing practices that have higher standards and are more carefully matched to conditions where mistakes will matter more.

Current information and computer-aided analytic methods are sufficient for layout of such a buffer system for many regions of the Sierra. An example is shown in figure 36.7 that illustrates a fixed buffer representing the energy area (150 ft) and the wider variable buffer area computed from the equation given earlier. Notice in the selected region along the North Yuba River near the town of Downieville that State Highway 49 lies within both areas for nearly all the distance illustrated. Stream channels in this case represent those modeled by GIS because existing USGS maps omit many actual streams. Refinements in scale of Digital Elevation Models from 30 m to 10 m are underway, and soil mapping (for estimating soil detachability and other factors) continues to expand and be incorporated into GIS layers. Most forest and land managers today could determine first approximations based on habitat requirements, energy inputs, and hillside slope calculations to produce a logical, ecologically based riparian management-protection system along these lines. It would lead to better protection of riparian-dependent organisms and of energy linkages between the land-water systems, and would assist managers in tailoring land-use activities to regions of greater need than is presently the case.

Riparian Maintenance Flows

The interrelations between physical channel processes and riparian vegetation are only now becoming better understood, and in any event the precise nature of these interrelations varies from river to river. Thus, specifying riparian maintenance flows (or "channel maintenance" or "flushing") can be viewed as essentially experimental at present.

To evaluate the effectiveness of riparian maintenance flows

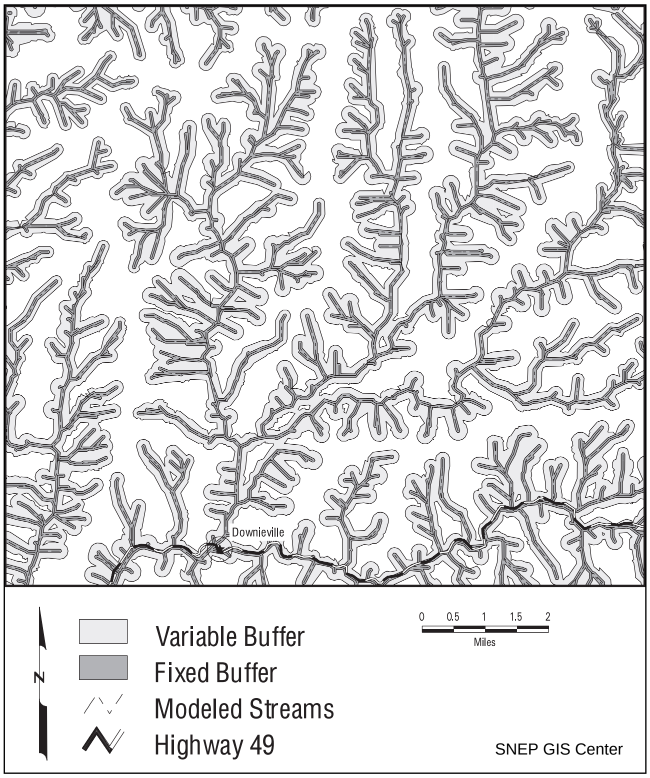


FIGURE 36.7

Fixed-width buffer (150 ft) and variable-width buffer computed from an equation for slope adjacent to stream channels for a region of the North Yuba River. Channel locations are determined from geographic information system models.

requires that the broad goal of maintaining riparian vegetation be restated as specific objectives from which flows can be specified and actual effects observed (Kondolf and Wilcock in press). For example, to maintain diversity of riparian habitat may require continued lateral migration of a meandering alluvial channel, which in turn requires adequate flows to erode banks and deposit point bars. Similarly, to prevent invasion of xeric plants onto bottomlands may require periodic flooding and high river stages that maintain seasonally high water tables. The magnitude of the flows required to achieve these objectives can be determined from stage-discharge relations by reach.

Hill and colleagues (1991) suggested that floods with a return period of 25 years under natural, predam conditions might be needed to maintain valley form and riparian habitat.

Restoration of Riparian Vegetation

Riparian revegetation projects may be limited to revegetation of banks to increase bank stability, channel shading, and overhanging vegetation. Artificial floodplains (essentially the second stage of two-stage flood channels), designed to be inundated every one to two years, are ideal sites to establish native riparian vegetation species (e.g. Matthews 1990). Much riparian revegetation has been undertaken to mitigate losses in riparian habitat elsewhere (Munro 1991), with mixed results in California. In general, riparian revegetation has been most successful along the banks of the low flow channel, less on higher surfaces. This difference is probably because of the nearly ubiquitous effect of reservoirs in reducing natural flood flows, eliminating hydrologic conditions needed for riparian vegetation on higher surfaces.

Probably the most ambitious riparian revegetation projects in the Sierra Nevada are being undertaken by the Nature Conservancy along the Cosumnes and South Fork Kern Rivers. Both rivers were chosen because their flood regimes are relatively natural, thus potentially maintaining near-natural hydrologic conditions on bottomlands.

Along the Cosumnes River, 80 ha (200 acres) have been replanted in valley oak (Quercus lobata) and other areas have been permitted to naturally revegetate in cottonwood (Populus fremonti) and various species of willow (Salix spp.). The suitability of various sites for different species was determined from flood inundation regime, soil type, and historical evidence of riparian vegetation present before these woodlands were cleared for agriculture (Griggs et al. 1994).

Along the South Fork Kern River, 130 ha (340 acres) were replanted, from 1987 to 1993 primarily, in Fremont cottonwood and red willow (S. lavigata) on floodplain sites from which these species had been cleared for agriculture. In large measure, the project was undertaken to create habitat for the yellow-billed cuckoo (Coccyzus americanus) and other avian species. Survival rates for plantings from 1991 to present have exceeded 90% (R. Tollefson, the Nature Conservancy, conversation with G. M. Kondolf, 1996).

CONCLUSIONS

Riparian areas are sites of exceptional ecological importance, typically having greater species diversity (floral and faunal) than surrounding uplands and providing essential food sources or habitat at certain life stages for upland wildlife species. Riparian areas also play a key role in maintaining water quality and aquatic habitat in streams and rivers, and because of their linear nature, riparian corridors are important routes for wildlife migration.

The riparian areas of the Sierra Nevada have been extensively affected by direct removal or inundation of riparian vegetation and by alterations to the conditions on which the riparian vegetation depends. Unfortunately, the field data base necessary to properly assess the health of riparian areas throughout the Sierra Nevada does not exist. However, from the extent of human activities known to affect riparian areas, we can infer substantial impacts. Moreover, map and aerial photograph analyses of a large sample of Sierran watersheds show that virtually all riparian corridors are interrupted by gaps caused by such human activities such as construction of road or railroad crossings, human settlements, dewatering of streams, grazing, timber harvest, and mining. The largest gaps are caused by reservoirs, many of which exceed 0.5 km (0.3 mi) in length, and which occur at a wide range of elevations in the Sierra Nevada.

Establishing riparian management zones (or "buffer strips") of adequate width is probably the single most effective strategy for protection and maintenance of the ecological values of riparian areas. Vegetation removal and ground disturbance should be prohibited in these zones, both to preserve the riparian habitat itself and for its beneficial influence upon aquatic habitat. Although the width of these zones has most commonly been set arbitrarily, variable-width buffer strips (based on attributes of the river itself, the riparian community, and hill-slope gradients) can be established to better protect riparian resources.

For channels below reservoirs, deliberate high flow releases can be made to mimic the hydrologic effects of natural floods in maintaining riparian vegetation. Restoration of riparian habitat, if based on careful analysis and on experience, can re-create many lost values to riparian and aquatic habitats.

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SECTION VI

Building Strategies for the Future Sierra Nevada

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Landscape-Level Strategies for Forest Fuel Management

ABSTRACT

As a result largely of human activities during the past 150 years, fires in Sierra Nevada forests occur less frequently and cover much less area than they did historically but are much more likely to be large and severe when they do occur. High-severity wildfires are considered by many to be the greatest single threat to the integrity and sustainability of Sierra Nevada forests. The continuing accumulation of large quantities of forest biomass that fuel wildfires points to a need to develop landscape-level strategies for managing fuels to reduce the area and average size burned by severe fires. Concurrently, more of the ecosystem functions of natural fire regimes—characterized in most areas by frequent low- to moderate-severity fires—need to be restored to Sierran forests. This chapter reviews past and current approaches to managing fuels on a landscape basis and, based on a synthesis of many of these approaches, proposes an outline for a potential fuel-management strategy for Sierra Nevada forests.

INTRODUCTION

Prior to concentrated Euro-American settlement in the middle to late 1800s, low- and middle-elevation forests in the Sierra Nevada were characterized by relatively frequent low- to moderate-severity fires (Skinner and Chang 1996). These frequent fires performed important ecological functions (Kilgore 1973). As a result largely of human activities during the past 150 years, including but not limited to fire suppression, fires now occur less frequently and cover much less area but are much more likely to be large and severe when they do occur (Husari and McKelvey 1996; McKelvey and Johnston 1992; Skinner and Chang 1996; U.S. Forest Service 1995; Weatherspoon et al. 1992). In aggregate, such high-severity fires are well outside the natural range of variability for these ecosystems and are considered by many to be the greatest single threat to the integrity and sustainability of Sierra Nevada forests. In addition, related human-induced changes in forest structure, composition, and processes (including many of the functions once performed by frequent fires) are in many areas so profound that they jeopardize ecosystem diversity and viability even without reference to severe fire (Skinner and Chang 1996; U.S. Forest Service 1995).

These concerns are prominent among the issues confronting those interested in the well-being of the Sierra Nevada. This chapter addresses potential landscape-level strategies intended to reduce the extent of severe fires in Sierra Nevada forests and to restore more of the ecosystem functions of frequent low- to moderate-severity fires. As a byproduct, these strategies offer tools that could contribute significantly to improving the health, integrity, and sustainability of Sierra Nevada ecosystems.

To keep the scope of the chapter manageable, we focus on the low- to middle-elevation coniferous forests of the Sierra Nevada, on both west and east sides of the crest. Our reasons include the following:

- These forests rank at or near the top among Sierran vegetation zones in terms of overall richness and diversity of resources and values.
- Twentieth-century fire occurrence in these forests has been much greater than in higher-elevation forests (McKelvey and Busse 1996). High-severity wildfires are much less a concern in the higher-elevation forests.

Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, Assessments and scientific basis for management options. Davis: University of California, Centers for Water and Wildland Resources, 1996.

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- Based on records of twentieth-century fire occurrence, the probability of wildfire in low- to middle-elevation coniferous forests is somewhat less than in the lower elevation foothill woodland and chaparral vegetation types (McKelvey and Busse 1996). However, the negative effects of severe wildfire on the dominant vegetation—and by extension on numerous other resources—generally are more profound and more long lasting in the coniferous forests.
- The composition and structure of the dominant vegetation in low- to middle-elevation coniferous forests probably have been affected more adversely by removal of the natural fire regime (and thus potentially could benefit more from its partial restoration) than in higher or lower vegetation types.

We recognize the problems associated with the threat of wildfires to lives and property in the urban-wildland intermix areas in the Sierran foothills. Management of foothill vegetation is mentioned in our discussion of these intermix areas. Many of the same general principles and approaches for fuel-management strategies that we discuss for the coniferous forests apply also to the foothill vegetation types.

A CAUTIONARY TALE OF FOREST BIOMASS

A simplified, qualitative accounting of production and disposition of biomass may help to clarify the problem of fuel accumulation in many Sierra Nevada forests. As indicated earlier, low- and middle-elevation forest types—west-side pine, west-side pine–mixed conifer, and east-side pine—are emphasized. It is appropriate here to consider only above-ground biomass, both for simplicity and relevance to the topic at hand. While we recognize the importance to today's forests of events in the latter half of the nineteenth century (McKelvey and Johnston 1992), we focus here on contrasts between the periods before 1850 and after 1900.

Biomass Production

Sierra Nevada forests produce a great deal of biomass. While considerable variation exists in terms of the site and climatic variables that largely determine net primary productivity, in general terms Sierra Nevada forests are quite productive (Helms and Tappeiner 1996). For the forest types indicated earlier, the west-side types are substantially more productive than east-side pine. The average rate of biomass production during most of the twentieth century probably has exceeded that which occurred from, say, 1650 to 1850 because this century generally has been warmer and wetter than the earlier period (Graumlich 1993). More complete site occupancy, in the form of denser forests in many areas (Gruell 1994), also may have contributed to greater production now than then. Allocation of total biomass production apparently has differed considerably between the two periods. A much greater percentage of biomass historically was stored in the boles of large trees and in herbaceous vegetation in relatively open stands, whereas now much more goes into small trees in dense stands.

Biomass Disposition

The main factors accounting for disposition or removal of forest biomass are decomposition (oxidation), fire (oxidation), and herbivores and humans (utilization).

Decomposition

In California's Mediterranean climate, decomposition rates generally are low, limited by low temperatures in the winter and inadequate moisture in the summer. In some portions of the Sierra Nevada mixed conifer forest type, however, sufficient moisture may be retained well into the summer to support fairly high rates of decay (Harmon et al. 1987). Decomposition rates in Sierra Nevada forests probably have been greater during this century than during the period 1650–1850 because (1) this century has been warmer and wetter (Graumlich 1993), (2) the generally denser stands during this century have provided more mesic microclimates that favor decomposition, and (3) more forest floor biomass has been available for decomposition because it has not been removed regularly by fire during the twentieth century. Neither historically nor now, however, has decomposition been the primary remover of biomass in Sierra Nevada forests.

Presettlement Fire

In presettlement forests most biomass ultimately was oxidized by frequent low- to moderate-severity fires. High-severity fires more than a few acres in size were unusual (Kilgore 1973; Skinner and Chang 1996; Weatherspoon et al. 1992). Across much of the landscape, dead biomass on the forest floor was kept at low levels, and most small understory trees were killed and subsequently consumed by fire. While small areas of high-severity fire killed patches of large trees (Stephenson et al. 1991), most large trees survived the fires and were consumed at some point after their death by subsequent fires. The longevity of large snags and downed logs under presettlement fire regimes is a subject of debate. It seems likely, however, that relatively few downed logs reached advanced stages of decay on xeric sites before being consumed by fire, whereas a greater proportion could last for longer periods (and also decay faster) on more mesic sites. Physical removal from the site was a minor component of total biomass disposition, although harvest of biomass by Native Americans, especially for firewood, may have been a significant factor locally (Anderson and Moratto 1996).

Twentieth-Century Fire

If we skip now to the twentieth century, the relative roles of fire and biomass removal have changed drastically. As fire suppression was initiated and took effect early in the century, the proportion of biomass consumed by fire dropped precipitously, as did annual burned area. During the course of the twentieth century, however, annual burned area for the Sierra Nevada has shown no overall time trend, even though it has fluctuated considerably from year to year. Large fires have composed an increasing proportion of that burned area as the century has progressed (McKelvey and Busse 1996). In recent years, large fires have become less controllable and more severe, evidently reflecting in part increased fuel loadings.

Another possible indicator of changing fuel conditions is a shift in the distribution of fires between human and lightning ignitions over the course of the twentieth century. We observed this shift as part of an evaluation of twentieth-century fire records for Sierran national forests. We used records for fires greater than 40 ha (100 acres) within the twenty-four core SNEP river basins. Because of the extraordinary extent of the 1987 and 1990 lightning fires, we present the summaries for two intervals of time so as to exclude and include these two years: 1910 through 1986 (table 56.1) and 1910 through 1993 (table 56.2). We arbitrarily split each interval into two time periods for these summaries.

These summaries suggest some conspicuous differences between human-caused fires and lightning fires. Whether the extraordinary years of 1987 and 1990 occurred simply by chance we cannot say based on these limited data. However, whereas the fire-suppression organization does appear to have reduced total area burned by, and number of, large human-caused fires, it has not been effective in reducing either the area burned by or the number of large lightning fires.

In table 56.3 we summarize fire characteristics for each of the three years of greatest burned area for each time period. All six of these years were quite dry. The summaries show that total area burned was similar in these years. However, lightning fires contributed only small proportions of total area burned for the first four years but very large proportions for the last two years—1987 and 1990. It is interesting to note that the total number of fires also differs considerably between the earlier years and 1987 and 1990. Those two years had fewer and much larger fires contributing most of the area burned.

The pattern of fire starts and the necessary response of the fire-suppression organization differ considerably between the two types of ignition. Human-caused fires generally occur as a singular event or occasionally a few simultaneous events. This allows the fire-suppression organization to respond to individual fires with a relatively large body of fire-suppression resources. Lightning fires, in contrast, usually occur as simultaneous multiple ignitions. In unusually dry years, resource requirements necessary to deal with simultaneous

TABLE 56.1

Summary of fire characteristics for 1910–47 compared with 1948–86.

	Total Annual Burned Area (ha)		Maximum Annual Fire Size (ha)		Total Annual Number of Fires	
Years	**1910–47**	**1948–86**	**1910–47**	**1948–86**	**1910–47**	**1948–86**
All Fires Greater than 40 ha						
Minimum	882	125	283	66	5	2
1st quartile	3,990	1,257	1,260	559	12	6
Median	14,483	4,295	3,324	2,026	19	9
3rd quartile	21,285	11,443	8,421	6,599	35	14
Maximum	95,126	43,330	21,234	18,100	82	23
Total for entire period	685,880	319,806			983	395
Human-Caused Fires Greater than 40 ha						
Minimum	882	125	283	66	5	2
1st quartile	3,732	1,182	1,022	553	11	5
Median	14,202	3,781	3,324	1,333	17	8
3rd quartile	20,708	8,690	8,421	6,599	33	11
Maximum	93,588	39,402	21,234	18,100	65	20
Total for entire period	651,801	273,526			890	318
Lightning-Caused Fires Greater than 40 ha						
Minimum	0	0	0	0	0	0
1st quartile	12	21	12	21	0	1
Median	324	217	175	197	2	1
3rd quartile	901	1,233	550	708	3	4
Maximum	9,738	7,356	5,748	7,238	18	6
Total for entire period	34,079	46,280			93	77

TABLE 56.2

Summary of fire characteristics for 1910–51 compared with 1952–93.

	Total Annual Burned Area (ha)		Maximum Annual Fire Size (ha)		Total Annual Number of Fires	
Years	**1910–51**	**1952–93**	**1910–51**	**1952–93**	**1910–51**	**1952–93**
All Fires Greater than 40 ha						
Minimum	828	44	283	44	5	1
1st quartile	3,990	1,178	1,260	526	12	6
Median	13,856	4,537	3,654	2,107	18	9
3rd quartile	20,110	12,125	8,880	6,144	34	13
Maximum	95,126	81,887	21,234	53,011	82	23
Total for entire period	730,131	454,861			1039	403
Human-Caused Fires Greater than 40 ha						
Minimum	828	0	283	0	5	0
1st quartile	3,732	1,120	1,022	481	11	4
Median	13,585	3,108	3,654	1,099	17	7
3rd quartile	19,585	6,993	8,880	4,434	32	9
Maximum	93,588	39,402	21,234	18,100	65	20
Total for entire period	692,170	267,879			934	306
Lightning-Caused Fires Greater than 40 ha						
Minimum	0	0	0	0	0	0
1st quartile	12	44	12	44	0	1
Median	324	347	175	272	2	1
3rd quartile	902	2,625	550	1,960	3	4
Maximum	9,738	80,704	5,748	53,011	18	13
Total for entire period	37,960	186,982			105	97

multiple ignitions can quickly exceed those available (e.g., 1977, 1987, 1990). Show and Kotok (1923) recognized early, on the basis of the 1917 fire season, that general regional lightning events have the potential to strain the fire-suppression organization severely.

The period of record is insufficient to conclude that there is a definite trend toward larger severe lightning fires or that a threshold has been crossed. However, we suggest that the potential influences of changing fuel mosaics, stand conditions, and landscape patterns on the fire environment logically would begin to show up first in dry years under lightning situations.

Utilization

In contrast to the changed role of fire in removing biomass, utilization of biomass has increased by orders of magnitude over the levels that prevailed before Euro-American settlement. The components of biomass removed by logging have changed dramatically from those that previously were removed by fire. Fire-resistant large trees have been harvested and replaced by much more fire-susceptible small trees. Dead biomass in the form of logging slash and natural (i.e., not produced by management activities) fuels has built up on the forest floor because of lack of fire and inadequate or nonex-

TABLE 56.3

Fire characteristics in the three major fire years (years of greatest burned area) during 1910–51 compared with those during 1952–93.

	1910–51			1952–93		
Year	**1924**	**1926**	**1931**	**1959**	**1987**	**1990**
Fire size (ha)						
1st quartile	95	101	119	155	182	120
Median	305	222	249	673	277	606
3rd quartile	1,307	572	1,095	3,268	785	3,405
Maximum	15,054	10,252	17,715	7,710	53,011	38,624
Total burned area	95,126	57,527	52,540	43,330	81,887	57,099
Lightning percentage[a]	2	17	2	9	99	95
Total number of fires	56	80	40	23	18	11

[a]Percentage of total area burned.

istent fuel treatment. Total decomposition probably has accelerated, but at a rate not nearly sufficient to compensate for the increasing fuel load. Together, surface fuels and dense understories have greatly increased the risk of crown fires (Kilgore and Sando 1975; Parsons and DeBenedetti 1979). Heightened stress from overly dense stands, often dominated by shade-tolerant species no longer kept in check by frequent fires, also has increased mortality from insects (Ferrell 1996), further adding to dead biomass available as fuel.

Fuel Management

As managers began to see the consequences of increased fuel loads, they undertook a variety of fuel-management activities. These activities have included a range of treatments that mimic or facilitate the natural processes of biomass disposition: (1) burning on site (with or without prior piling or rearrangement), (2) accelerating decomposition (and reducing flammability) by rearranging the fuel bed closer to the ground, and (3) physical removal from the site. Adequacy of slash treatment following timber harvest or other vegetation management activity has varied from quite good to nonexistent.

For the Sierra Nevada as a whole, however, vegetation management activities have produced considerably more new fuels than they have eliminated. Furthermore, the increasing problem of live understory fuels has been addressed inadequately in silvicultural or fuel-management activities. Efforts to treat accumulating amounts of natural fuels, often with prescribed fire, also have fallen far behind rates of fuel accretion, due in large part to inadequate funding and various concerns about the use of prescribed fire. Even the active prescribed burning programs in Sierran national parks over the past twenty-five years, utilizing both natural and management ignitions, have restored fire to the forests at rates well below presettlement levels (Botti and Nichols 1995; Husari and McKelvey 1996; Parsons 1995). Consequently, these burns have been unable even to keep up with new biomass accumulation, let alone to consume all the excess biomass generated by decades of fire suppression. The basic problem is the same outside the parks: current quantities of flammable biomass—primarily small trees and surface fuels—in low- to middle-elevation Sierran forests are unprecedented during the past several thousand years and are continuing to accumulate at a much faster rate than they are being removed.

The Fuel Problem and the Need for a Strategy

Given current federal and state budget climates, increasing suppression costs, and attrition of skilled firefighters, reductions in suppression forces seem more likely than substantial increases (Husari and McKelvey 1996; U.S. Department of the Interior and U.S. Department of Agriculture 1995). According to a growing consensus among fire managers, more suppression capability is not the solution anyway. This idea is reinforced, we believe, by the data presented earlier on distributions of lightning and human ignitions. History tells us that periodic dry years are inevitable and that regional-scale lightning events that limit the effectiveness of suppression forces are not unusual.

If more suppression is not the answer, and if flammable biomass continues to accumulate at current rates, and if we do nothing substantive to arrest that accumulation, simple physics and common sense dictate that the area burned by high-severity fires will increase. Losses of life, property, and resources will escalate accordingly. This conclusion is strengthened by the fact that recent "drought" years, during which many large, severe fires burned (McKelvey and Busse 1996), appear to be relatively common when viewed on a time scale of centuries (Graumlich 1993).

Therein lies the rationale for large-scale fuel management. Given the massive scope of the problem and budget constraints, brute force is likely to be neither feasible nor adequate. A carefully considered strategy is required. Treatments need to begin in the most logical, efficient, cost-effective places. Specific components of biomass—mostly small trees and surface fuels—need to be targeted. We must devise ways to pay for the needed treatments. At least on public lands, treatments conducted to reduce the hazard of severe wildfires should be compatible with overall desired conditions for sustainable ecosystems. In general, conditions need to be moved away from dense, small-tree-dominated forests toward more open, large-tree-dominated forests. And the rate of treatment needs to be carefully planned: in the short term, rates of biomass removal may well need to exceed rates of production in order to return these forests to a more sustainable, fire-resilient condition. The remainder of this chapter displays and discusses various considerations for developing such a landscape-level fuel-management strategy.

A REVIEW OF FUEL-MANAGEMENT STRATEGIES

Our use of the term *fuel-management strategies* here refers to methods for prioritizing or locating fuel treatments on a landscape scale in such a way as to increase their overall effectiveness for reducing the extent of severe wildfires. Most past fuel management in the Sierra Nevada has taken place in the national forests. Most of that has not been characterized by strategic planning: management emphasis and funding have directed fuel management primarily toward treatment of activity fuels following timber sales, and sales usually were not located with strategic fuel considerations in mind. In fact, timber sales often were dispersed—thereby reducing overall effectiveness of fuel treatments—intentionally in an attempt to meet various management objectives, such as minimizing cumulative watershed impacts of harvest-related activities. In recent years, however, innovative fire and fuel managers have begun to think much more strategically and to collaborate with foresters and silviculturists to address landscape-level forest health concerns. This change has been stimulated and supported by the general move toward ecosystem management and by new capabilities for spatial, landscape-level planning provided by geographical information system (GIS) technology.

Some of these evolving ideas are included in the following sections, which provide a sampling of various types of fuel-management strategies that have been proposed and, to varying degrees, implemented. Also incorporated here are some of the ideas discussed by a group of experts in a Fuels Management Strategies Workshop sponsored by SNEP in March 1995 (Fleming 1996). Three somewhat distinct but certainly overlapping approaches have been used: (1) identifying fuel-management approaches appropriate within each of several landscape zones defined by general characteristics, uses, or emphases; (2) setting priorities based on various combinations of risk, hazard, values at risk, and suppression capabilities; and (3) employing a fuelbreak-type concept intended to interrupt fuel continuity on a landscape scale and to aid in limiting the size of fires by providing defensible zones for suppression forces. A fourth “approach” that has received explicit emphasis recently, although it is implicit to some degree in the other approaches, is rate or timing of implementation.

Strategies Based on Zones

Arno and Brown (1989) proposed three landscape zones. In Zone I, wilderness and natural areas, the emphasis would be on prescribed natural fire (PNF), augmented by management-ignited prescribed fires (MIPF) as necessary to restore much of the natural role of fire to these ecosystems. In Zone II, the general forest management zone, well-planned and well-implemented fuel management, both in conjunction with and in addition to proper timber harvests, would contribute significantly to good overall management. In Zone III, the residential forest, education of homeowners and local officials about the realities of fire hazards in the wildland-urban interface would go hand in hand with effective, esthetically pleasing manipulation of fuels. The authors suggested that shaded fuelbreaks around homes and developments could be an effective measure. They recommended concentrating most efforts in Zone III and adjacent portions of Zone II.

A somewhat different zone approach provides the basis for fire-management direction in Sequoia–Kings Canyon National Parks (Manley 1995) . Zones are defined by estimated proximity of current conditions to the natural range of variability. In Zone 1, areas essentially unaffected by postsettlement activities (mostly higher elevations), natural processes, including PNF, are permitted to operate with little restriction. In Zone 2, areas significantly modified by postsettlement activities, corrective actions, including conservative use of PNF and MIPF, are required before permitting resumption of all natural processes. In Zone 3, built-up areas with highly flammable fuel types near park boundaries, full suppression is combined with mechanical fuel treatments and conservative use of MIPF.

Greenwood (1995) described a land classification system based on structure density (presumably closely related to population density) plus appropriate fire-related buffers. While his analysis was done for the entire state of California, the subset of Sierra Nevada data could easily be analyzed separately, and most of his general conclusions probably would still apply. He labeled the classes wildland, intermix, and developed, corresponding to increasing structure densities, and noted the surprisingly high percentage of land in the intermix category, even on public lands. He emphasized that the presence of people and their structures constrains many of the options available for both fuel management and fire suppression. Approaches suggested ranged from reestablishment of presettlement conditions and processes in some wildland areas to reliance on fire-safe regulations, public education, aggressive initial attack, and only minimal vegetation manipulation in more densely settled developed areas.

Strategies Based on Risk, Hazard, Values at Risk, and Suppression Capabilities

To provide a common frame of understanding for the discussion that follows, definitions of “risk,” “hazard,” and “values at risk” (McPherson et al. 1990) are given here.

> FIRE RISK: (1) The chance of fire starting, as affected by the nature and incidence of causative agents . . . (2) Any causative agent. (P. 45)
>
> FIRE HAZARD: A fuel complex, defined by volume, type, condition, arrangement, and location, that determines the degree of ease of ignition and of resistance to control. (P. 42) “Resistance to control” is related both to fire behavior and resistance to line construction.
>
> VALUES-AT-RISK: Any or all natural resources, improvements, or other values which may be jeopardized if a fire occurs. (P. 131)

A number of authors have reported the use of decision analysis to aid in fuel-management decision making (Anderson et al. 1991; Cohan et al. 1983; Radloff and Yancik 1983). Decision analysis became the cornerstone of the National Activity Fuel Appraisal Process (Hirsch et al. 1981; Radloff et al. 1982), which was intended to provide a consistent means of evaluating the important factors affecting fuel-treatment decisions. The Fuel Appraisal Process provided probabilities of various-sized fires by intensity class, based on information about topography, historical weather, historical fire occurrence (risk), suppression capability, and hazard (measured or projected based on alternative fuel treatments).

Biehl (1995) described an “all risk management” strategy in use on the Stanislaus National Forest. Fuel profiles, expected ignitions, and suppression resources are used in conjunction with management-defined acceptable resource loss to determine whether, where, and what kind of fuel treatment is needed. The Stanislaus National Forest is combining the most active prescribed burning program of all California national forests—concentrated mainly in natural (i.e., nonactivity) fuels—with considerable biomass thinning. Fuelbreaks are employed, but only as anchor lines to facilitate initiation of areawide fuel treatments using prescribed fire.

Perkins (1995) has devised a similar fire-analysis system for use on the Klamath National Forest as part of the forest's landscape-analysis system. Risk, fire behavior potential (based on fuel classification, slope class, and ninetieth-percentile summer wildfire weather conditions), and resource values (based on forest plan direction) are the primary factors used to determine fuel-management treatment priorities. Fuels information is derived from vegetation classification, modified by management history and large-fire history.

James (1994) developed a simple system for estimating a "catastrophic fire vulnerability rating," based on a point total derived from separate qualitative assessments of risk, hazard, value, and suppression capability. The system includes three sets of "fire/fuel treatment standards" corresponding to fire vulnerability ratings of high, moderate, or low. Finally, it provides a straightforward feedback mechanism for adjusting the posttreatment vulnerability rating. All vulnerability factors are weighted equally, but local managers should be able to modify weightings fairly easily to account for their assessment of the relative importance of various factors.

Strategies Based on Fuelbreaks or Similar Landscape-Level Interruptions of Fuel Continuity

> FUELBREAKS: Generally wide (60–1,000 feet) strips of land on which native vegetation has been permanently modified so that fires burning into them can be more readily controlled. (McPherson et al. 1990, 56)

Early Experiences with Fuelbreaks

Green (1977) traced the long history of fuelbreaks and their predecessors, firebreaks (narrower strips usually cleared to mineral soil), in California. Perhaps surprisingly, a recommendation to the State Board of Forestry for blocking out the forest with strips of "waste" land wide enough to prevent fire from crossing was made as early as 1886. The Sierra Nevada was a part of early firebreak history. S. B. Show, District Forester, proposed in 1929 that a firebreak be constructed along the entire length of the western slope of the Sierra Nevada at the interface of the chaparral and the pine forest. Depression-related federal funding, especially for the Civilian Conservation Corps, permitted work to begin in 1933 on what came to be known as the "Ponderosa Way and Trucktrail." The intent of this strip, which when completed was about 1,050 km (650 mi) long and generally 45–60 m (150–200 ft) wide (Green 1977), was to help prevent fires from burning from the chaparral up into the more valuable Sierran timber (Green and Schimke 1971).

The transition from firebreaks to fuelbreaks came about as part of preattack planning in the early 1950s (Green 1977). Most early fuelbreak construction was in southern California chaparral. The Duckwall Conflagration Control Project on the Stanislaus National Forest, initiated in 1962, extended the fuelbreak concept into the Sierra Nevada mixed conifer forest type (Green and Schimke 1971). Green and Schimke (1971), Pierovich and colleagues (1975), and Green (1977) provided a number of guidelines for planning, constructing, and maintaining fuelbreak systems. Among their recommendations: The number and location of fuelbreaks, along with the size of blocks to be separated by the fuelbreak network (1,000 ha [2,500 ac] for the Duckwall program), should be determined by fire-control objectives as part of the preattack planning process. Needs for protecting populated areas or high resource values should be given high priority in fuelbreak location. Planned management projects—in range, wildlife, recreation, timber, watershed, and forest roads and trails—should be reviewed to see how they might contribute to the fuelbreak network. Ridges usually are preferred for locating fuelbreaks, although other locations can be used. Locating fuelbreaks along existing roads where possible was recommended to facilitate access by suppression forces. Suggested fuelbreak widths varied from about 60 to 120 m (200 to 400 ft). The necessity of maintaining reduced-fuel conditions on fuelbreaks, through a combination of appropriate vegetation (e.g., low volume and/or low flammability) and periodic treatments, was emphasized.

A number of anecdotal accounts of the effectiveness of fuelbreaks (or lack thereof) during wildfire incidents, mostly during the 1960s and early 1970s, were summarized by Pierovich and colleagues (1975) and Green (1977). Although experiences were mixed, fuelbreaks were found to be effective much of the time in stopping wildfires except under the most extreme conditions. Success was most likely when fuelbreaks were properly installed, properly maintained, and adequately staffed by suppression forces during wildfires.

The same authors (Pierovich et al. 1975; Green 1977) discussed existing economic analyses of fuelbreak effectiveness, which differed in their conclusions but for the most part found that a fuelbreak system could be justified economically as part of a well-integrated fire-management system. A subsequent study of fuelbreak investments in southern California, using a linear programming model, predicted that increasing fuelbreak widths could substantially reduce area burned and fire-related damages if initial investments were concentrated in a specific "damage-potential zone" (Omi 1979). Although potential corollary—i.e., nonfire—benefits of fuelbreaks have been recognized (Green 1977), such benefits generally have not been considered in evaluations of their efficacy or cost effectiveness. In a study of three forested fuelbreaks in the central Sierra Nevada, however, Grah and Long (1971) found that fuelbreak construction increased timber values within the fuelbreaks by reallocating site resources to larger, faster growing, and more valuable trees. A portion of fuelbreak costs, therefore, was offset by the benefit to the timber resource.

Recent Experiences and Recommendations for Using Fuelbreaks

Fuelbreak construction and maintenance have retained some emphasis in southern California. Salazar and Gonzalez-Caban (1987) found that in a large 1985 wildfire in chaparral on steep terrain, the fuelbreak system apparently influenced the location of the final fire perimeter. Except during the most extreme burning conditions, fuelbreaks functioned as intended.

In contrast, most forested areas in the state have seen little attention given to fuelbreaks over the past twenty years. Fuel management in Sierra Nevada national forests has been dominated by support of the timber management program during most of that period. Budgets for other fuel activities have been quite limited. Furthermore, many fire and fuel specialists have viewed fuelbreaks as being of little value for a variety of reasons, including the following: (1) to be effective for stopping fires, fuelbreaks need to be staffed by suppression forces, which often have been unavailable when needed, frequently because of demands for protecting structures in urban-wildland intermix areas; (2) in general, recommended fuelbreak widths of 60–120 m (200–400 ft) (Green and Schimke 1971; Green 1977) have been considered too narrow to be effective under many conditions, especially with extensive spotting (ignition of new fires outside the perimeter of the main fire by windborne sparks or embers); (3) fuelbreaks often have been viewed as standalone measures that competed with more effective areawide fuel treatments; and (4) fire control has been viewed as the sole beneficiary of fuelbreaks, with little thought given to other potential resource benefits.

Over the past ten years or so, a number of large, severe fires in California and elsewhere in the western United States have emphasized the seriousness and the enormity of the wildland fuel problem. Fuelbreaks have begun to receive renewed attention as one part of the solution. Arno and Brown (1989) suggested their use around homes and developments in the wildland-urban interface. In the recovery plan for the northern spotted owl, Agee and Edmonds (1992) recommended the use of fuelbreaks along with underburning to reduce the probability of catastrophic wildfires in "designated conservation areas" within the Klamath and East Cascades subregions. Weatherspoon and colleagues (1992) suggested a two-stage fuelbreak strategy to help reduce the occurrence of severe fires in California spotted owl habitat in Sierra Nevada mixed conifer forests. Known owl sites first would be "isolated" using a broad band of prescribed burns, followed by a more general program of breaking up fuel continuity on a landscape scale. Fites (1995) proposed a similar approach to help protect "areas of late-successional forest emphasis" and to restore more sustainable, fire-resilient conditions across the landscape. Arno and Ottmar (1994, 19) pointed out the need for "an interconnected network of natural fire barriers and treated stands as zones of opportunity for controlling wildfires."

In the draft Environmental Impact Statement (EIS) for managing California spotted owl habitat in Sierra Nevada national forests (U.S. Forest Service 1995), Alternatives C and D included an upper slope/ridge zone that would be dominated by large, widely spaced shade-intolerant trees. These alternatives were viewed as creating conditions in this zone closer to those thought to have existed before Euro-American settlement. In addition, the zone would provide many of the fire-management benefits of a wide shaded fuelbreak. Alternative F incorporated some of the fuelbreak-related concepts of the Quincy Library Group (QLG) proposal (summarized later) for the northern Sierra Nevada.

LaBoa and Hermit (1995) presented a number of ideas for strategic fuel planning and treatment, based on their recent work as members of the California spotted owl EIS Team (sufficiently recent that these ideas were not included in the draft EIS). They included the use of fuelbreaks; however, they stressed the need not to stop with a fuelbreak network but to build from it to accomplish large-scale fuel modification on a landscape level.

The most detailed fuel-management strategies to date have been proposed for the northern end of the Sierra Nevada—the Lassen and Plumas National Forests and the Sierraville Ranger District of the Tahoe National Forest. The two strategies, which were developed semi-independently by the QLG and the U.S. Forest Service, have much in common and build on many of the ideas cited earlier. Rapid implementation of a network of broad fuelbreaks is key to both proposals.

QLG is a community-based group whose members represent a wide range of interests, including fisheries and environmental groups, timber industry, and county government. The group has made strategic fuel management a central focus of its land management proposal (Quincy Library Group 1994). QLG proposes that an intensive four-year effort be focused on installing a network of strips approximately 0.4 km (0.25 mi) in width, mostly along existing roads, that break up fuel continuity across the landscape and provide defensible zones for suppression forces. During this period, essentially all forest management activities, including biomass and other thinnings, salvage activities, and treatment of surface fuels, would be focused on implementing this fuelbreak network. Each year 1/32 of the total forest acreage would be treated, so that at the end of the four-year period 1/8 of the forest would be a part of these strips. The strips would have reductions in stand density, lower canopy ladder fuels, and surface fuels, and they would have relatively low levels of snags and large downed woody debris. After the initial period, a longer term fuel-management strategy would add some strips to isolate areas of high value and/or high risk, but the emphasis generally would shift to areawide treatments.

The Technical Fuels Report, prepared by fire/fuel specialists from the Lassen, Plumas, and Tahoe National Forests (Olson et al. 1995), is similar in several respects to the QLG proposal. The "defensible fuel profile zone" (DFPZ), a concept first described by Olson (1993), is central to the strategy outlined in the report. Much like a broad fuelbreak, a DFPZ is a low-density, low-fuel zone averaging 0.4 km (0.25 mi) in width, located mostly along roads, and designed to support suppression activities. Like the strips in the QLG proposal, DFPZs are intended to be installed over a period of just a few years. The authors point out that DFPZs are intended not to take the place of widespread fuel treatment but rather to increase the effectiveness of initial fuel treatment and to facilitate subsequent treatment of adjacent areas. Olson et al. (1995) describe the "community defense zone" (CDZ) as another component of their strategy concerned with urban interface areas within or near national forest boundaries. Similar in concept to a DFPZ, a CDZ is designed to reduce the threat of wildfire spreading onto national forest land from private land, or vice versa. Like DFPZs, CDZs would have a high priority for completion within a short period of time. The authors stress the importance of the involvement and cooperation of local communities in implementation of CDZs. A third type of zone, the "fuel reduction zone" (FRZ), refers to general area fuel treatment that would take place mainly after the high-priority system of DFPZs and CDZs is in place. The Technical Fuels Report (Olson et al. 1995) emphasizes the importance of site-specific considerations and local decision making in setting priorities and implementing the details of the broad fuel-management strategy outlined.

A POTENTIAL FUEL-MANAGEMENT STRATEGY FOR SIERRA NEVADA FORESTS

The approaches summarized in the previous section, along with the discussion at the SNEP Fuels Strategies Workshop (Fleming 1996), seem to point to some degree of convergence of thinking about the fuel problem and some components of a strategy to deal with it. In this section we attempt to synthesize many of the previously mentioned approaches into an outline for a potential fuel-management strategy for Sierra Nevada forests.

The ideas presented here are necessarily general in nature. The Sierra Nevada is enormously complex and diverse. Landowners and ownership objectives vary widely. While agencies and large landowners may choose to set some priorities on a regional or subregional scale, any attempt on our part to recommend or prescribe specific management practices rangewide would be naive, counterproductive, and contrary to the SNEP charter. Readers should view this "strategy" as a set of principles and ideas to consider as they develop their own landscape-specific strategic plans. (Additional ideas can be found in cited references.) Such plans will be greatly facilitated and improved by developing and maintaining good GIS databases. Later in this chapter we discuss the nature and role of such databases for supporting fire and fuel-management decision making in the context of adaptive ecosystem management (Everett et al. 1994; Walters and Holling 1990).

Although landscape-specific planning is focused on a small portion of the entire Sierra Nevada, it nevertheless requires thinking on a much broader scale than often has occurred in the past. Making significant progress toward these goals will require long-term vision, commitment, and cooperation across a broad spectrum of land-management agencies and other entities. Dealing with fuels on only a local, piecemeal basis will be inadequate.

Goals of the Fuel-Management Strategy

The strategy has three general goals, ranging from short to long term and from relatively narrow to broad. Each goal can be viewed as nesting within the following one. The goals are consistent and complementary, as are the means to work toward their accomplishment. For example, the strategy provides that short-term approaches to reducing hazard be compatible with longer-term goals of ecosystem sustainability (Arno and Ottmar 1994).

The first goal—the immediate need from a fire-management standpoint—is to reduce substantially the area and average size burned by large, severe wildfires in the Sierra Nevada. Ideally this will be a short- to medium-term goal, whose urgency will lessen as the fuel-management strategy becomes increasingly effective. A second, longer-term goal should be to restore more of the ecosystem functions of frequent low- to moderate-severity fire. The two goals are closely linked. They could be met simultaneously by replacing most of the high-severity acreage with the same, or preferably much greater, acreage of low- to moderate-severity fire. A third, overarching goal is to improve the health, integrity, and sustainability of Sierra Nevada ecosystems. This goal certainly goes beyond fire considerations. Progress toward achieving the first two goals, however, is critical to the third.

Management actions to progress toward these three goals should be occurring concurrently. Often it will be possible for a single treatment or project to address all three goals simultaneously. In fact, opportunities for such congruence should be sought. In this chapter, however, we spend the most time addressing the first goal—not because it is most important in the long run but because it is the most urgent in the short run to reduce losses of lives, property, and resources, and to make it possible to work more effectively toward achieving the second and third goals. Stated in another way, the fuel-management strategy has joint themes of protection and restoration of ecosystems, and, in many portions of the Sierra Nevada, protection is a prerequisite to restoration. In a longer term context, strategies geared specifically toward reducing losses from large, severe wildfires should gradually become less important; restoration in turn should provide a more fundamental level of protection along with improved ecosystem health.

Goal 1: Reduce Substantially the Area and Average Size Burned by Large, High-Severity Wildfires

Large, high-severity fires were unusual historically in most Sierra Nevada forests. Fire regimes in the Sierra Nevada generally were characterized by relatively frequent, low- to moderate-severity fires (Skinner and Chang 1996). Changes in low- and middle-elevation forests and their associated fuel complexes, brought about largely by human activities since Euro-American settlement (including but not limited to fire suppression), have made these forests much more prone to large, severe fires (Chang 1996; Husari and McKelvey 1996; McKelvey and Johnston 1992; Skinner and Chang 1996; U.S. Forest Service 1995). Such fires, in aggregate, are well outside the natural range of variability and thus can be considered detrimental to Sierra Nevada ecosystems (Manley et al. 1995). Furthermore, the current prevalence of such fires is unacceptable socially. The rapidly increasing population of the Sierra Nevada increasingly places people's houses at risk of loss to severe wildfires and makes potential solutions to the problem much more difficult.

In pursuing goal 1, it is essential for the wildland fire agencies to continue support for suppression and prevention activities. These fire-management efforts alone, however, cannot resolve the problems of fire in the Sierra Nevada. Aggressive, strategically logical fuel-management programs, compatible with overall desired conditions for sustainable ecosystems, are necessary to address the basic problem of excessive fuel accumulation.

Goal 2: Restore More of the Ecosystem Functions of Frequent Low- to Moderate-Severity Fire

The frequent low- to moderate-severity fires that occurred throughout much of the Sierra Nevada until about 150 years ago performed many important ecological functions (Kilgore 1973; Chang 1996). Wildfires of this type, however, have been virtually eliminated from Sierra Nevada ecosystems (as measured by annual area burned by such fires), because these are the fires that are suppressed most easily. As a result, the ecological functions historically performed by such fires have been largely lost, with some known and many unknown consequences. It is highly unlikely that fires will ever burn as much area as often and with the same distribution of severities as they once did. Nevertheless, it makes sense to try to restore fire to a more nearly natural role in those parts of the landscape where it is practical to do so. Where fire alone cannot be used practically, fire surrogates such as silvicultural techniques and mechanical fuel reduction methods (Helms and Tappeiner 1996; Weatherspoon 1996) can be employed—either by themselves or in conjunction with prescribed fire—as appropriate to mimic some of the functions of fire and to move landscapes toward desired conditions (Manley et al. 1995). Over time, adaptive management (Everett et al. 1994; Walters and Holling 1990) should help us to determine which ecosystem functions of fire can be emulated satisfactorily by surrogates, which may be irreplaceable, and the implications for management.

Goal 3: Improve the Health, Integrity, and Sustainability of Sierra Nevada Ecosystems

The third goal is consistent with the first two and is central to overall SNEP goals. It should be achievable (1) by reducing the incidence of high-severity fires, which are detrimental to ecosystem sustainability in natural fire regimes characteristic of most of the Sierra Nevada; and (2) by moving ecosystems closer to pre-European-settlement conditions and processes, assumed by many to be a useful first approximation of sustainable ecosystems (e.g., Manley et al. 1995; Swanson et al. 1994), at least on public lands. We cannot define those presettlement conditions with any great precision, but we do know enough to be reasonably confident that this strategy would move us in the desired direction.

Components of the Strategy

The strategy we discuss here has three basic components: (1) networks of defensible fuel profile zones (DFPZs) (the term adopted from Olson 1993 and Olson et al. 1995) created and maintained in high-priority locations; (2) enhanced use of fire for restoring natural processes and meeting other ecosystem management goals; and (3) expansion of fuel treatments to other appropriate areas of the landscape, consistent with desired ecosystem conditions. We also discuss possible institutional changes that might increase the effectiveness of the strategy. This strategy builds upon and draws freely from the various strategies cited elsewhere in this chapter.

Defensible Fuel Profile Zones

Given the massive scope of the problem that goal 1 is intended to address, a carefully considered strategy is required for prioritizing fuel treatments. Such a strategy should permit managers to multiply the benefits of treatments in order to make the most rapid and most efficient progress toward achieving goal 1. We focus our discussion in this section on DFPZ networks. Multiple benefits of DFPZs may include (1) reducing severity of wildfires within treated areas (as with any fuel-management treatment), (2) providing broad zones within which firefighters can conduct suppression operations more safely and more efficiently, (3) effectively breaking up the continuity of hazardous fuels across a landscape, (4) providing "anchor" lines to facilitate subsequent areawide fuel treatments, and (5) providing various nonfire benefits. We are aware of no other strategy with as great a potential in the short term to progress reasonably rapidly toward achieving goal 1.

Rationale

The basic purposes of fuelbreaks were summarized earlier. These stated purposes generally do not include some of the potential benefits we envision for DFPZs, however. We offer an expanded rationale here, including the reasons for our choosing not to use the term fuelbreak as part of the strategy we describe.

Fuel-management activities in forested ecosystems normally involve some combination of (1) removing or modifying surface dead fuels to reduce their flammability; (2) removing or modifying live fuels to reduce their horizontal and/or vertical continuity, thereby reducing the probability of crown fire; and (3) felling excess snags that could be safety hazards and sources or receptors of firebrands.

The kind of protection afforded by fuel-management treatments depends not only on the localized nature of the treatments but also on their scale and spatial relationships. If you do a good job of treating fuels on a 1-acre (0.4 ha) patch of forest but do nothing in the surrounding forest, the edge effects probably will overwhelm the treatment in the event of a severe fire, and the small patch will be lost as well as everything around it. (There is a lesson here for group selection cuttings [Helms and Tappeiner 1996; Weatherspoon 1996]: it makes little sense to do fuel treatments in only the small regeneration openings and ignore the rest of the forest [Weatherspoon and Skinner 1995].) If you treat fuels to the same standard in a square 40-acre (16 ha) stand, edge effects are relatively much less important. Fire intensity will be much lower than in the surrounding (untreated) forest, and under most conditions the majority of the stand probably will survive. However, that 40-acre stand probably will have only a limited effect on fire damage in the untreated forest downwind. If you now treat the fuels on n 40-acre stands scattered randomly across the landscape, essentially the same result is expected, times n—i.e., the treated stands probably will not suffer excessive damage from a fire, but their intensity-reducing effect will not extend much beyond the treated areas. This last scenario, incidentally, approximates most of our past fuel treatments, which were not planned with strategic fuel management in mind.

If you take that same total treated acreage (40n) and string it together into a broad zone (DFPZ) that makes sense strategically, you have still protected those treated acres, with even less edge effect. In addition, however, you now have a reasonable chance of putting suppression forces into that zone and stopping the fire, thereby protecting areas on the downwind side of the DFPZ.

The term fuelbreak or shaded fuelbreak has been used to describe some of the same ideas. We do not use either term in describing this strategy, however, because they tend to carry some undesirable connotations:

- A shaded fuelbreak is often envisioned as a strip of land too narrow (60–120 m [200–400 ft] [Green and Schimke 1971; Green 1977]) to be effective for stopping a fire under many conditions. In contrast, 0.4 km (0.25 mi) has been suggested as a nominal width for DFPZs (Olson et al. 1995; Quincy Library Group 1994). Use of the term zone (the Z in DFPZ) suggests a broader treated area than fuelbreak.
- A shaded fuelbreak is usually considered to have a single purpose—a relatively safe, accessible location in which suppression forces can initiate suppression actions. A DFPZ also serves this suppression function, almost certainly more effectively (because of its greater width) than a normal shaded fuelbreak. In addition, however, the DFPZ represents a substantial portion of the landscape—perhaps 10 to 25 percent for a completed network—within which fire damage is likely to be much reduced in the event of a wildfire. Furthermore, a DFPZ network may represent a number of potential additional benefits, including improved forest health, greater landscape diversity, increased availability of open forest habitat, and probably greater proximity to the historic range of variability and desired conditions.
- A shaded fuelbreak is often envisioned as "an alternative"—i.e., a standalone option for dealing with fuels. The DFPZ incorporates the notion that landscape treatment of fuels must start somewhere, so it makes sense to begin in strategically logical locations. The DFPZ is a place to start—a place from which to build out in treating other appropriate parts of the landscape—not an end in itself.

General Location, Description, Creation, and Maintenance

For the most part, DFPZs should be placed primarily on ridges and upper south and west slopes. All else being equal, DFPZs should be located along existing roads to simplify construction and maintenance and to facilitate use by suppression forces. Where roads do not follow ridges, road locations in relatively gentle terrain—e.g., along broad valley bottoms—are usually suitable for DFPZs. Roads that follow side slopes and canyon bottoms in steep terrain should be avoided except where they might facilitate stream crossings by DFPZs.

A network of DFPZs that define discrete blocks of land would require some DFPZ segments to cross drainages. Decisions about how best to deal with stream crossings should be based upon site-specific analyses. In most cases, however, we anticipate that the function of a DFPZ network would not be seriously jeopardized by limiting any treatments within the riparian zone portion of a DFPZ to those treatments (if any) deemed acceptable elsewhere in the riparian zone. Prescribed burning might be particularly appropriate as a treatment. Because of their relatively moist environment, untreated or minimally treated riparian zones normally should not present an undue risk of serving as a "fuse" to spread fire across a DFPZ adequately staffed with suppression forces.

A reasonable nominal width for DFPZs is probably 0.4 km (0.25 mi) (Olson et al. 1995; Quincy Library Group 1994) until experience indicates otherwise. It seems logical, however, to vary the width based on strategic importance, topography, or other conditions. For example, a broad, major ridge with a main road might warrant a considerably wider DFPZ than a spur ridge with steep side slopes. Using the fire-growth model FARSITE to model various fuel-treatment alternatives, van Wagtendonk (1996) found that fires burning under ninety-fifth-percentile weather conditions spotted across 90-m (300 ft) fuelbreaks under most fuel treatment scenarios but did not spot across 390-m (slightly less than 0.25 mile) fuelbreaks under any of the scenarios.

The Quincy Library Group (1994) proposed that DFPZs be used to break up the land into blocks averaging 4,000–5,000 ha (10,000–12,000 ac). We have no reason to argue with that as a first approximation, but the appropriate area certainly will vary among landscapes as a function of topography and the various factors discussed later. In many cases it may be logical to implement an initial high-priority "low-density" DFPZ network—e.g., along major ridges and main roads and in the vicinity of forest communities. Subsequent efforts would be a combination of maintaining existing DFPZs, constructing new ones to break up the landscape into smaller blocks, and broadening existing DFPZs in conjunction with areawide fuel treatments.

Treatment of DFPZs should result in a fairly open stand, dominated mostly by larger trees of fire-tolerant species. DFPZs need not be uniform, monotonous areas, however, but may encompass considerable diversity in ages, sizes, and distributions of trees. The key feature should be the general openness and discontinuity of crown fuels, both horizontally and vertically, producing a very low probability of sustained crown fire. Similarly, edges of DFPZs need not be abrupt but can be "feathered" into the adjacent forest. Posttreatment canopy closure usually should be no more than 40%, although adjustments in stand density based on local conditions certainly are appropriate. In some areas, for example, greater canopy closure may be desirable to slow encroachment by highly flammable shrubs or other understory vegetation, so long as tree crowns are high enough that a sustained crown fire in the denser canopy is very unlikely.

Available treatment techniques for DFPZs include silvicultural cutting methods, prescribed fire, mechanical fuel-reduction techniques, and combinations of these. In most cases, cuttings of various kinds will be the most effective initial treatments to accomplish needed adjustments in stand structure and composition (Helms and Tappeiner 1996; Weatherspoon 1996). Thinning from below often will be a desirable technique to move DFPZs from overly dense, small-tree-dominated stands toward more open, large-tree-dominated stands. Prescribed fire frequently will be the treatment of choice following a cutting. In some areas, prescribed fire alone may be the preferred approach because existing stand conditions are near desired conditions or because cuttings are precluded or otherwise inappropriate. Generally, however, prescribed fire is not likely to be a suitable standalone technique for bringing about major changes in stand structure on the large scale necessary for timely implementation of DFPZ networks in Sierra Nevada coniferous forests. Factors that argue against massive and rapid increases in standalone prescribed burning include lack of adequate funding (initial burns in unthinned stands may be quite expensive), air-quality restrictions, competition for trained personnel during active wildfire seasons, and risk of escapes. Moreover, needed reductions in stand density using fire alone could require a number of successive burns spanning several decades. Failure to utilize biomass in the process would generate large quantities of smoke from consumption of excess biomass and would forgo opportunities to generate income to finance treatments. Opportunities for economic and social benefits would be forfeited as well. Furthermore, effects of initial burns probably would not closely approximate "natural" fire effects because of fuel complexes that differ greatly from those of the presettlement era (Skinner and Chang 1996; Weatherspoon 1996).

To ensure effectiveness of a DFPZ, basic adjustments in stand structure must be followed by reduction in surface fuels to a low-hazard condition using prescribed fire or mechanical methods, or both. In some cases, adequate mechanical "treatment" may result from crushing of fuels during harvest operations, especially where whole trees are removed from the stand. Prescribed fire was the best choice among van Wagtendonk's (1996) modeled scenarios from the standpoint of reducing surface fuels, and it also can raise the bases of live crowns (by killing lower branches) to increase vertical discontinuity of live fuels. Where feasible economically, removal and utilization of cut trees are preferable to treating them in place as fuels. Densities of snags and downed logs should be kept relatively low and compensated as appropriate by higher densities outside DFPZs.

From a fire standpoint, ridges and upper southerly slopes generally should benefit more than average from thinning and hazard reduction: they tend to dry out faster and without treatment would support severe fires a higher proportion of the time than other aspects and slope positions. The heavy thinning also would promote faster growth of trees into large size classes less susceptible to fire damage. Their low-fuel character, low density of snags, and resistance to sustained crown fires should make DFPZs substantially safer for suppression personnel than most other locations. Furthermore, the efficiency and productivity of suppression forces in building and holding firelines and in backfire operations should be significantly enhanced in DFPZs, especially in those containing roads. Aerial retardant drops should be considerably more effective in DFPZs as well because of the open canopy and relative ease of getting retardant to the forest floor.

To retain their effectiveness, DFPZs should be maintained in low-fuel conditions with periodic retreatments, targeting especially accumulated surface fuels and new growth of understory vegetation. Retreatment with prescribed burns should be relatively easy and inexpensive in the open environment of DFPZs. (It should be noted in this regard that

DFPZs are not unique in their need for maintenance. Fuel treatments anywhere require maintenance to retain their effectiveness. A DFPZ should cost less to maintain than an equal area of comparable fuel treatment elsewhere, however, because of its contiguity and relative accessibility.) Burns may be required about once every ten years or more often depending on rate of encroachment by shrubs and other understory fuels. DFPZ retreatment may be combined with broadened area treatment, using the DFPZ as an “anchor line.” Appropriate vegetative ground covers, including perennial grasses and low-volume shrubs (e.g., bear clover), can reduce maintenance needs (Green 1977).

As main canopy trees grow and increase in crown area, they will need to be thinned periodically to maintain desired crown spacing. A few may be left to become snags, but snag density generally should be lower than elsewhere in the forest. In addition, long-term maintenance of a large-tree-dominated DFPZ will require periodic regeneration of portions of the zone. Long-rotation, low-density versions of group selection (Weatherspoon 1996) might be the best silvicultural method for this purpose, because it provides for regeneration of shade-intolerant (generally fire-tolerant) species and permits the maintenance of single canopy layers in any given location, thereby discouraging crown fires. With long rotations, a DFPZ could have sustainable age-class structures and still be occupied mostly by fire-resistant large trees.

Potential Nonfire Benefits

A range of benefits not directly related to fire would be expected to accrue from having more open stand conditions along ridges and upper southerly slopes. In general, such open conditions probably would be somewhat similar to those that dominated the same topographic positions in presettlement forests (Skinner and Chang 1996)—on average more open than other sites because of more xeric conditions and more frequent fires. A probable reduction in total evapotranspiration could lead to increased water yield from these sites. Probability of adverse watershed effects from harvesting and other management activities should be reduced because of greater-than-average distances from streams (Kattelmann 1996). These areas should contribute to overall habitat diversity and esthetic variety in landscapes that currently tend to be deficient in open, large-tree-dominated structures (Graber 1996; U.S. Forest Service 1995). Forage conditions should be improved in more open forest areas, especially with prescribed fire (Menke et al. 1996), and conceivably could help to reduce livestock grazing pressure in riparian areas. From a timber standpoint, total production of woody biomass might be reduced but would be concentrated in larger, more valuable trees (e.g., Grah and Long 1971). Lower stand density should reduce stress on trees and make them less susceptible to insect attack (Ferrell 1996). It is possible, though unproved, that broad zones of relatively low susceptibility to insects could reduce “contagion” effects of insect activity, thus perhaps slowing movement of outbreaks (Mason and Wickman 1994). If found to be true, this idea would provide an interesting parallel to the effect of a low-hazard DFPZ on fire movement.

The concept that DFPZs may have multiple nonfire benefits emphasizes the point that strategic fuel management is an integral component of overall ecosystem management. It also argues for focusing a large proportion of overall management efforts in the short term on planning and implementing a sound DFPZ network.

Factors to Be Considered in Prioritizing DFPZ Locations

In the next sections we present a number of factors that should be considered in designing a DFPZ network. We do not attempt to set priorities among these factors—to presume, for example, that values should be weighted more heavily than historical fire occurrence or that one value is more important than another value. Such prioritization is best left to local managers using local fire planning and other information.

“Biggest Bang for the Buck.” This concept says, in essence, “All else being equal, do the cheapest, easiest areas first.”

Some stands already may be in an open, low-fuel condition because of recent management activities. Other areas, such as rocky outcrops and relatively bare ridges, may provide natural barriers to the spread of fire. Where it makes sense strategically to do so, such areas should be incorporated into a DFPZ network.

For areas requiring some degree of treatment to be suitable as a DFPZ, we suggest that those areas sometimes considered “most in need of treatment”—i.e., dense stands and heavy fuels—should not necessarily be given high priority. Their costs per unit area may be quite high. This subject can, and should, be debated. Our feeling, however, is that from a strategic standpoint, it seems advisable to treat first those areas that currently would not function effectively as a DFPZ but that could be brought to acceptable standards most quickly and inexpensively. Thus a greater total length of effective DFPZ could become functional for a given cost or in a given period of time. That larger treated area of DFPZ also would be more likely itself to survive in the event of a severe fire.

Some areas may be acceptably open but require surface fuel treatment. Prescribed burning may be the most desirable and cost-effective option. More often, some thinning is likely to be necessary. Except in areas where they are precluded for various reasons, cuttings (preferably with utilization of cut trees) generally provide a more efficient route to desired forest structures than prescribed burns. Where thinning is needed, the “biggest bang for the buck” principle may translate to giving priority to multiproduct sales that are economically self-sustaining by removing some sawtimber to pay for the removal of smaller trees.

Other examples of locations or conditions that might be given priority under this principle include (1) accessible areas with relatively gentle terrain and (2) areas with a significant component of relatively large pine or Douglas fir trees.

An additional benefit of the "biggest bang for the buck" principle may be in more quickly developing demonstration areas or other examples of successful implementation of DFPZs. Such areas may be valuable for building and sustaining trust and support for strategic fuel management.

Historical Fire Occurrence and Risk. A major consideration in locating DFPZs on the landscape should be the broad zones within the Sierra Nevada that have experienced the highest occurrence of large fires during this century—reflecting a combination of relatively high risk and high hazard. McKelvey and Busse (1996) found a strong elevational trend in the occurrence of twentieth-century fires in Sierran national forests. The frequency (percentage of area burned at least once) of large fires was highest below 1,000 m (3,300 ft) elevation and dropped fairly rapidly at higher elevations. This elevation zone corresponds generally with the foothill vegetation types and lower coniferous forests. It is consistent with observations by others that the highest twentieth-century fire occurrence in Sierra Nevada forests has been in the west-side pine and pine–mixed conifer types and in the east-side pine type (LaBoa and Hermit 1995; U.S. Forest Service 1995; Weatherspoon et al. 1992).

This information suggests a fairly simple guideline for accounting for historical fire occurrence: all else being equal, and in the absence of more site-specific fire-occurrence information, begin establishing a DFPZ network at the lowest elevations of ponderosa or Jeffrey pine forests and work upward into the mixed conifer type. In the general forest zone—i.e., away from settlements or other high-value areas—true fir and other upper montane types probably have low priority for a DFPZ network from the standpoint of wildfire control. Certainly other management objectives, however, may call for zones of more open forest conditions than those common in most locations today.

Where managers have good "landscape-specific" data on fire-occurrence, it of course should be weighed more heavily than regionwide trends. Local fire data also may indicate the direction of prevailing winds that accompany extreme weather events and/or large fires; this information should be used in planning DFPZ locations. Current and projected information on risk—i.e., ignition sources—should be considered as well. For example, DFPZs should have a role in isolating heavily traveled transportation corridors and other areas where ignitions historically have been high. This certainly applies to urban-wildland intermix areas, which are discussed next.

Urban-Wildland Intermix Areas. DFPZs have a potential benefit as protective buffers around high-value locations. Urban-wildland intermix areas are prominent in this regard. A protective buffer should help reduce the incidence of fires moving from wildlands into these high-value areas and (from the risk standpoint) also reduce the movement into wildland areas of fires initiating in intermix areas. These reasons, along with the fact that most populated areas in the Sierra Nevada lie within the elevation zone most frequently burned during the twentieth century (Greenwood 1995; McKelvey and Busse 1996), give a high overall priority to strategic fuel management in urban-wildland intermix areas.

As compared with DFPZs elsewhere, in forested intermix areas it may be desirable to focus more on nonfire silvicultural treatment methods in order to minimize concerns about smoke and potential escapes. In woodland and chaparral vegetation types, however, prescribed burning may be the most practical treatment approach except for limited areas of mechanical treatment. Opportunities may exist for the California Department of Forestry and Fire Protection's Vegetation Management Program (Husari and McKelvey 1996) to develop DFPZs near urban-wildland intermix areas in conjunction with some of its prescribed burning in foothill vegetation types.

The need to deal with fire and fuel issues in intermix areas is confounded by the considerable complexity of those issues. The physical problems associated with the juxtaposition of people, personal property, and wildlands are compounded by an array of problems linked to political and institutional conditions, multiple and diverse ownerships, and a wide range in understanding and attitude.

Any overall fuel strategy for urban-wildland intermix areas must begin with the use of appropriate fire-safe practices by individual property owners. Prominent among those practices are adequate clearance between structures and flammable vegetation and the use of fire-resistant roofing and other fire-safe construction practices (Davis 1990). Part of the process of achieving better compliance with fire-safe regulations is simply education of property owners—necessarily an ongoing task. Another part may involve stronger incentives, including significant fines for noncompliance, revision of insurance premiums and insurability requirements (Davis 1990), and possibly increased tax rates, to reflect more accurately the risk of fire loss in wildland settings as modified by personal fire-safe practices.

Cooperative efforts to reduce hazard within and around communities represent another critical component of fuel management in intermix areas. Partnerships that include local governments, local landowners, community groups, bioregional councils, and, as appropriate, state and federal agencies could be effective. Fostering such cooperative efforts is a high priority for the recently formed California Fire Strategies Committee. Sponsored by the California Resources Agency, the committee consists of representatives of a wide array of government and private entities with a common interest in dealing effectively with California's wildfire problems. Members have adopted an ambitious set of action items in support of the committee's mission "to reduce the risk of catastrophic fire for the protection of Californians and the natural environment."

Fuel-management activities in urban-wildland intermix areas should be coordinated with similar activities on nearby national forest or other public land and with activities of large private landowners. In a recent strategic assessment of fire management in the U.S. Forest Service, Bacon and colleagues (1995) proposed that priority for hazard mitigation on national forests in intermix areas be placed on areas where adjacent landowners agree to participate with the U.S. Forest Service in fuel management and other fire-safety projects. While designing and implementing an effective DFPZ network in and around complex intermix areas often will not be easy, it will be greatly facilitated by effective cross-ownership cooperative efforts.

Concerns about intermix areas do not stop with current conditions. Population in Sierran foothill areas is projected to continue rapid growth (Duane 1996). An important potential set of solutions related to fire issues rests with state and local officials, including legislators and county planning and zoning commissioners, who should implement appropriate limitations and disincentives for new construction in high-fire-hazard areas.

Fire-related connections between urbanized areas and nearby wildlands go beyond the potential spread of fire from one area to the other. Increasingly in recent years, federal wildland fire-control agencies have been put into the position of having to assume responsibility for structure protection during major wildfires (Bacon et al. 1995; Husari and McKelvey 1996). This imposes costs on other landowners and the general public in two ways: (1) Taxpayers at large pay for these fire-protection services, and (2) losses to natural resources on public lands increase when these forces are diverted to structure protection (Davis 1990). Bacon and colleagues (1995, 4) proposed a redefinition of responsibilities: "(1) fire protection on State and private lands is the responsibility of State and local governments, (2) homeowners have a personal responsibility to practice fire safety, (3) the role of the Forest Service is stewardship of adjacent National Forests, cooperative assistance to State and local fire organizations, and cooperative suppression during fire emergencies." They suggested two general approaches for the U.S. Forest Service in response to these responsibilities: (1) The U.S. Forest Service would phase out of responsibility for direct initial attack in urbanized areas. Existing protection agreements would be renegotiated to reflect this change. Cooperative fire-protection programs would be expanded to facilitate state efforts to take on the additional work. (2) Protection priorities would be changed from the present order of life first, property second, and resources third, to life first, followed by property and resources valued on a par. These recommendations are consistent with policy changes for federal agencies proposed in the Federal Wildland Fire Management Policy and Program Review (U.S. Department of the Interior and U.S. Department of Agriculture 1995). Bacon and colleagues (1995) also recommended that opportunities be sought for land exchanges that would improve the ability to manage fire in urban-wildland intermix areas.

Other High-Value Areas. A number of other kinds of high-value areas may warrant buffering with DFPZs—e.g., areas of late-successional emphasis (Franklin et al. 1996), biodiversity management areas (Davis et al. 1996), and plantations (Wilson 1977). Such protection may be particularly useful when fuel reduction within the high-value area itself is undesirable or infeasible because of the nature of the value being emphasized and/or high costs of treatment. It might be desirable to treat a high-value area with prescribed fire, for example, but appropriated funds might be inadequate, especially since initial reintroduction of fire without mechanical pretreatment can be rather expensive in some places. In contrast, a DFPZ outside the high-value area could be self-financing through removal of a product. It also could aid in the subsequent reintroduction of fire into the area.

DFPZs need not be placed immediately adjacent to a high-value area. In most cases it probably is desirable to back off to a location that makes sense for other reasons, as discussed earlier—e.g., a ridge or an upper south slope, along a road, relatively cheap to treat.

Using a DFPZ to provide a buffer between adjacent areas may also be useful where management emphases or intensities, rather than values per se, differ. For example, it might be desirable to provide such a separation between an area managed primarily for natural values, including use of PNF, and an adjacent area managed primarily for commodities. This might or might not be associated with an ownership boundary.

Fire Hazard. Hazard is another factor that needs to be considered in locating DFPZs. All else being equal, a landscape dominated by continuous heavy fuels is in greater need of zones of fuel discontinuity than one with light fuels. Insofar as possible, however, actual DFPZ location should favor relatively open, low-fuel sites in order to treat more area with the available funds. In other words, DFPZs should separate high-hazard areas but not necessarily be built through them.

It is reasonable to assume that high-hazard areas may be relatively more of a concern with respect to the potential for high-severity wildfires in drier years. In such years, a higher percentage of the total fuel profile (including live fuels) becomes readily available for combustion. Drier fuels and drier microclimate near the forest floor favor easier ignition and faster fire spread. The significance of such changes in dry years is increased by the preponderance of dry years in the past ten years and by the fact that such years may be more nearly the norm when viewed on a time scale of centuries (Graumlich 1993).

Professional and Public Support. Many forest-management activities are controversial, among resource professionals as well as various segments of the public. We believe that creating and maintaining DFPZs may offer multiple benefits, including reduced wildfire hazard, improved forest health, and utilization of excess forest biomass, which in most cases should outweigh potential ecosystem damage. Adequately explained and understood, therefore, DFPZs should be reasonably well supported. Nevertheless, some areas proposed for DFPZs may be controversial. All else being equal, we suggest that, at least initially, creation of DFPZ networks be concentrated in areas where professional and public support are relatively high and disagreement relatively low. In most cases, more than enough work will need to be done to permit activities to be focused in these areas and to defer more controversial work. Well-designed and properly implemented early DFPZs may generate additional support for further development of a strategic fuel-management program.

Rate of Implementation and Practicability

We believe that, in the short term, planning and implementing DFPZ networks should have a high priority for management of low- to middle-elevation Sierran forests and appropriate portions of foothill woodland and chaparral types. Ideally, these networks should be in place within ten years. Implementing these networks will require a great deal of concentrated and cooperative effort. It also may well require “departures” from nondeclining even flow of timber volume under the National Forest Management Act. Potential benefits could be substantial, however, in terms of strategic reduction of wildfire hazard, improvement in forest conditions, and increases in economic and social well-being in forest-based communities.

By any measure, implementing a rangewide system of DFPZs within ten (or even twenty) years is a formidable undertaking. Responsible managers must be concerned with the feasibility and potential value of such a task compared with alternative management actions. Given the high priority of fire-protection and restoration issues in Sierran forests and the multiple benefits (cited earlier) that might be anticipated from DFPZ networks, a number of managers may judge such networks to have a high overall priority for management.

To be achievable, implementation of a DFPZ system cannot be viewed simply as a fire function or goal. Rather, it should be considered a multiresource or ecosystem management goal, with much of the overall activity of the management unit in the short term being integrated with and focused on planning and implementing a sound DFPZ network. Similarly, multifunction funding would improve the feasibility of accomplishing this task.

How will we pay for all the silviculture and fuel management that will be necessary to implement DFPZ networks, given the large areas that need to be treated? Considering historical levels of funding and current directions of federal budgets, it seems highly unlikely that federal appropriated funds—even from multiple functions—will be adequate. And managers may decide that most of the limited appropriated funds for fuel treatment are best spent to support prescribed burning of natural fuels in areas with special emphases on reestablishing natural processes (see the following section). Thus, truly significant progress on DFPZs and other large-scale fuel treatments will have to be the result of economically self-sustaining activities. Yet much of the needed treatment involves removal of small trees that often have marginal or negative market value. Part of the solution may come from multiproduct sales, in which sawtimber and other high-value products subsidize the removal of lower value material. One of the challenges for managers will be to locate and design multiproduct or other sales in ways that make them economically viable. In addition, however, it probably will be important to support the establishment of particleboard or other plants capable of generating value from small trees. Public land managers and private entrepreneurs need to discuss whether and how it may be possible to provide sufficient assurances of a continuing supply of biomass from public lands (e.g., for several decades) to warrant the capital investment in such plants. Research and development efforts also are needed to develop more efficient technology for harvesting and processing small material and new markets for utilizing it (Lambert 1994).

Most resource professionals would agree that fuel reduction and thinning of overly-dense stands are high-priority needs in most pine and mixed-conifer forests of the Sierra Nevada. These are precisely the kinds of activities envisioned for DFPZs, with the added proviso that they be placed in strategically logical locations. It is important to note, therefore, that the major barriers to DFPZ implementation—e.g., economic viability of small trees and maintenance of treated areas—are not unique to DFPZs: they apply much more widely. Thus, these barriers must be resolved in any case if large-scale thinning and fuel management are to be implemented. The contiguous nature and relative accessibility of DFPZs, however, may help to lessen the severity of these problems in DFPZs.

Enhanced Use of Fire

Restoring the many functions of fire as an ecosystem process can be accomplished fully only by using fire. Alternative and supplementary methods must play a large part in needed restoration, but they can substitute only partially for fire (Weatherspoon 1996). In the context of goal 2, therefore, we believe that a considerably expanded use of prescribed fire can and should play an important role in the management of Sierra Nevada ecosystems (Husari and McKelvey 1996; Mutch et al. 1993).

In some portions of the Sierra Nevada, especially higher elevation areas, large high-severity fires are not much of a concern. Thus neither goal 1 nor DFPZs are particularly applicable. Many such areas are located in national parks and wilderness areas, but substantial additional acreage of red fir and other high-elevation vegetation types fits in this category. Our suggestion in these areas would be to extend the use of prescribed natural fire (PNF) as much as possible (including appropriate areas outside parks and wildernesses) and to augment PNF with management-ignited prescribed fires

(MIPF) as needed to reestablish a near-natural distribution of fire frequencies.

MIPF also should become a key part of the management of other areas in which restoration of natural processes is a major management objective. Examples of such areas might include areas of late-successional emphasis (Franklin et al. 1996), biodiversity management areas (Davis et al. 1996), and research natural areas.

As indicated earlier, DFPZs require periodic maintenance to retain their effectiveness, and prescribed fire often will be the treatment of choice. Since the structure and composition of DFPZs are intended to be closer to presettlement conditions than most other areas of the landscape, it would seem logical for fire to assume a dual role there—maintenance of the low-fuel nature of DFPZs and restoration of natural processes.

A number of practical and political considerations constrain the use of both MIPF and PNF on a large scale. Constraints include risk of escapes, lack of adequate funding, competition for trained personnel during active wildfire seasons, and air quality restrictions (Husari and McKelvey 1996; Parsons 1995). The difficulties of applying prescribed fire on a significant scale are illustrated by the inability of the prescribed fire program at Sequoia and Kings Canyon National Parks—certainly among the most active in the Sierra Nevada—even to begin to approach the presettlement fire frequency for the giant sequoia groves. A National Interagency Fire Center study to be undertaken beginning in 1996 will test the feasibility of and constraints on landscape-scale application of prescribed fire in the Kaweah River drainage of Sequoia National Park.

In addition to prescribed burning, significant benefits related to goal 2 could be achieved by allowing low- and moderate-intensity wildfires to burn. Potentially, many more burned acres could be achieved by this means than with prescribed fire. The vast majority of ignitions in the Sierra Nevada are suppressed using fast, aggressive control. The flexibility already existing in present federal fire-management policy to use alternative suppression responses is rarely exercised outside the national parks and a few wilderness areas in the Sierra Nevada (Husari and McKelvey 1996). Fire managers currently are required to select the most economically efficient suppression option without considering potential resource benefits of wildfires. Fires that would produce results most similar to those that occurred under presettlement conditions are regularly suppressed while small, because they are easy and inexpensive to put out. Proposed new federal policies (U.S. Department of the Interior and U.S. Department of Agriculture 1995) would permit wildfires to be "managed" if they meet resource objectives.

More flexible use of appropriate suppression responses, possible use of managed wildfires to meet resource objectives, and expanded use of both MIPF and PNF jointly offer considerable opportunities for managers to restore more of the ecosystem functions of fire to the Sierra Nevada. All of these opportunities should be enhanced as forest and fuel conditions are improved over time. It should be recognized that in those areas from which fire continues to be excluded, for whatever reasons, some ecosystem components and processes will depart significantly from their natural range of variability, with unknown consequences.

Areawide Fuel Treatments

The development of DFPZs described in this chapter is a logical place to begin, but it is intended to be only a first step toward achieving the three goals of the fuel-management strategy discussed earlier. DFPZs should help to limit the spatial extent of severe fires (van Wagtendonk 1996; Sessions et al. 1996); however, they will not reduce the susceptibility of the intervening landscape areas to severe fire effects, nor will they improve forest health or restore more nearly natural processes in those intervening areas. Landscape mosaics and vegetative profiles will need to be managed on broader scales, using mainly silvicultural cuttings and fire, to achieve desired forest conditions and processes (Mutch et al. 1993).

The implementation of areawide landscape treatments should be significantly facilitated by using previously established DFPZ networks as anchor lines from which to build out. Factors considered in prioritizing DFPZ locations, discussed earlier, may also be useful as guides for prioritizing areawide treatments. From the standpoint of topography, for example, middle and upper south and west aspects on relatively gentle (machine-operable) slopes may be logical locations for early work.

RESEARCH AND ADAPTIVE MANAGEMENT NEEDS

The Role of Adaptive Management

Ecosystem management is increasingly espoused as a guiding concept for managing public lands (Jensen and Bourgeron 1994; Manley et al. 1995; Salwasser 1994). Managing for ecosystem integrity and sustainability, however, is more difficult and fraught with more uncertainties than managing for a set of specific outputs. We have much to learn. For many reasons, including the complexity and variability of forested ecosystems and the broad spatiotemporal scale that provides the context for ecosystem management, traditional research cannot provide all the answers. Scientists, managers, and interested members of the public must work together as partners in a process of learning by doing—i.e., adaptive ecosystem management (Everett et al. 1994; Mutch et al. 1993; Walters and Holling 1990).

A key concept of adaptive management is that we cannot wait for perfect information, because we will never have it. Despite the uncertainties, we must move forward with managing for sustainable ecosystems using the best information we have, knowing that with time we will learn more and be able to manage more intelligently.

The subject of landscape-level fuel-management strategies is certainly appropriate to address through adaptive management. For example, we can make educated assumptions about how a network of DFPZs might help to reduce high-severity fires and contribute to desired conditions and landscape diversity. Only through monitoring, experience, and time, however, will we know the validity of those assumptions. Only through adaptive management will we learn what locations, target conditions, and treatment schedules for implementing a DFPZ network will work for what kinds of landscapes—or whether a DFPZ network makes sense in the first place.

Similarly, we know that the ecosystem functions of frequent low- to moderate-severity fire have been largely lost from Sierran forests. Restoring these functions can be accomplished fully only by using fire. Yet in many areas silvicultural techniques and other fire "surrogates" are needed in addition to or in lieu of fire to accomplish needed restoration (Weatherspoon 1996). The extent to which natural fire regimes can or should be emulated, and the consequences for long-term ecosystem viability of alternative approaches to using fire versus fire surrogates on large scales, will become clear only through carefully designed research and adaptive management.

A GIS Database in Support of Fuel-Management Strategies and Adaptive Ecosystem Management

Good information is essential to intelligent planning of specific fuel-management strategies in the short term, and to assessing the effectiveness of those strategies (and adjusting subsequent management as appropriate) in the mid to long term. An integrated GIS database can provide a good focus for this information. The concept is quite simple and logical, given the increasingly GIS-oriented world in which we operate. Actually accomplishing the monitoring and other data collection necessary to make it fully functional may be another matter. From a fire standpoint, it probably makes sense to use the same general priorities for this data collection as discussed earlier for locating DFPZs.

In the following sections we indicate some thoughts about the directions in which we should be moving with GIS databases. We are not suggesting a standalone fire and fuel GIS. Rather, the following kinds of data needed to support fire and fuel decision making would be integrated into a larger database to inform overall land management.

Management Direction

Management objectives and guidelines, including those specific to fire and fuel management, should be indicated by area.

Vegetation and Fuels Data

The need for data on vegetation and fuels is basic and well recognized. (Much of the living vegetation is fuel, of course, but to simplify the discussion here we list vegetation and fuels separately.) Mapping should utilize the best sampling strategies combining remote sensing imagery (perhaps at several scales) and ground truthing. The reliability of existing vegetation maps should be verified before they are incorporated into the database. Fire-relevant attributes of vegetation (including understory composition and structure, and vertical and horizontal continuity) need to be characterized adequately. Similarly, surface fuels should be described, utilizing field-verified vegetation / fuels correlations to the extent feasible.

Since vegetation and fuels change over time, the dynamics occurring naturally through succession and growth must be dealt with using models combined with periodic field evaluations. Natural and human-caused disturbances also change vegetation and fuels, from a little to a lot. The database must be updated as needed to reflect these disturbance-induced changes. To account for these dynamics adequately, we need to go beyond traditional spatial GIS to incorporate new concepts in spatiotemporal GIS (Peuquet 1994; Skinner et al. 1992).

Management Activities and Other Disturbances

For our land management activities (including prescribed fire and fuel management) that significantly alter vegetation and fuels, monitoring must be carried out to determine the extent to which management objectives were met and the effects on vegetation, fuels, and other key ecosystem components. The GIS database should be updated to indicate the nature, date, spatial extent, and costs of the activity and the resulting spatially referenced vegetation and fuels. "Natural" or unplanned disturbances—especially wildfires—must also be incorporated into the database. Wildfires should be mapped by severity classes and key fire effects. To the extent allowed by available data, burning conditions at different times and places on a fire, along with suppression actions and costs, also should be entered. After postfire activities are completed, the new vegetation / fuel complex should become part of the database. To permit long-term evaluation of fires and management activities, however, it is important to maintain—not discard—prefire vegetation and fuel data. A spatiotemporal GIS would serve this purpose more efficiently than the systems generally available today (Peuquet and Niu 1995; Peuquet et al. 1992).

Other Fire-Related Data

Risk (historical fire occurrence and historical and projected ignition patterns), values at risk (for both populated and wildland areas), suppression capabilities, and any other spatially relevant fire-planning data should be included in the database. It may well be advisable for public and private landowners to cooperate in establishing data standards and protocols applicable to fire and fuels, thereby permitting data sharing, cross-ownership analyses, and the like when mutually desirable.

Benefits of the GIS Database

This kind of database, in even a rudimentary form, certainly will permit better planning for fuel-management strategies. As data are improved and accumulated over time, moreover, its value will increase. We will begin to have the data necessary to relate wildfire severity and effects to prior management activities (including fuel treatments), fuel conditions, and site and stand characteristics (e.g., Weatherspoon and Skinner 1995). Over time, as more wildfires are documented, our ability to assess the efficacy and cost-effectiveness of various fuel-management strategies in terms of both behavior and effects of subsequent wildfires and suppression costs will grow. We also will be able to evaluate trade-offs involving environmental effects of the treatments themselves. We will be much better able to learn by doing and monitoring—the essence of adaptive management (Everett et al. 1994; Mutch et al. 1993; Walters and Holling 1990).

Establishing and maintaining an accurate GIS database of this kind will require considerable effort and commitment on the part of managers and landowners. It will be a long-term, ongoing process. Many other resource benefits will accrue, however, and in fact it is difficult to see how real ecosystem management in a fire-prone region such as the Sierra Nevada will be feasible without such a database.

CONCLUSIONS

Fire has been an important component of most Sierran ecosystems for thousands of years (Skinner and Chang 1996). However, human activities since European settlement, along with variation in climate, have profoundly altered fire regimes, leading to anomalous vegetation and fuel conditions throughout much of the range. Two major fire-related "problems" have developed in the Sierra Nevada: (1) too much high-severity fire and the potential for much more of the same and (2) too little low- to moderate-severity fire, along with a variety of ecological changes attributable at least in part to this deficiency. Clearly, these are not just "fire problems." They influence virtually all resources and values in the Sierra Nevada and cut across all of SNEP's subject areas.

Given the realities of our modern civilization, we must recognize that the changes in ecosystem conditions and in the role of fire are only partially reversible. We can and should reduce the extent of large, severe wildfires. However, such fires will continue at an appreciable level (almost certainly at a higher level than in the presettlement period) into the foreseeable future. We can and should restore more of the ecosystem functions of low- and moderate-severity fire, utilizing such fire to the extent feasible. It is inconceivable, however, that fire in its presettlement extent and frequencies could be restored fully to the Sierra Nevada.

Nevertheless, a partial solution is far better than no solution at all or than a continuing deterioration of Sierran forests from a fire standpoint. There is much that we as land stewards can and should do. The two fire-related problems cited earlier can be translated into the three strategic goals that have been discussed in this chapter. Making significant progress toward these goals will require long-term vision, commitment, and cooperation across a broad spectrum of land-management agencies and other entities. The problems were created over a long period of time, and they certainly cannot be solved overnight. Progress also will require landscape-scale strategic thinking, planning, and implementation. This chapter has provided some ideas for managers to consider as they develop their own landscape-specific plans.

We have much to learn as we move more fully into an era of ecosystem management, including strategic fuel management. Adaptive management must be an integral part of our management activities, as discussed earlier. It is important to note in this regard that we do not have to have all the answers before beginning needed restoration work. We know enough at this point to recognize that current conditions in most low- to middle-elevation forests of the Sierra Nevada are unacceptable in terms of wildfire hazard, diversity, and sustainability. Regardless of the extent to which presettlement conditions are used as a guide to desired conditions, most informed people would agree that these forests generally should be less dense, have less fuels, and have more large trees. Even if we have not precisely identified target conditions, we certainly know the direction in which we should begin moving. That beginning alone will require a large measure of commitment and hard work. We can adjust along the way as we learn more and become better able to define desired conditions for Sierran forests.

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